A Multilepton Signal For Supersymmetric Particles in Tevatron Data?

R. Michael Barnett$^1$ and Lawrence J. Hall$^{1,2}$.

$^1$ Lawrence Berkeley National Laboratory
University of California, Berkeley, California 94720

$^2$ Department of Physics
University of California, Berkeley, California 94720

Abstract

The CDF and D0 collaborations have both reported unusual events in the dilepton+jets sample with very high lepton and missing transverse energies. It is possible, but very unlikely, that these events originate from top quark pair production; however, they have characteristics that are better accounted for by decays of supersymmetric quarks with mass in the region of 300 GeV: $\tilde{q} \rightarrow q\tilde{\chi}, \tilde{\chi} \rightarrow \nu\tilde{\ell}, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$. Such a supersymmetric origin also leads to events with large transverse missing energy and either 0, 1, 2 same-sign, or 3 isolated leptons.

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In Run I of the Tevatron Collider, the CDF and D0 collaborations announced the discovery of the top quark in a variety of channels [1]. Production of \( \bar{t}t \), with \( t \to bW \) and both \( W \)'s decaying leptonically leads to \( \ell^+\ell^-jjE_T \) events where \( \ell \) is an energetic, isolated \( e \) or \( \mu \), \( E_T \) is missing transverse energy and \( j \) represents a jet. In 110 pb\(^{-1} \), the CDF Collaboration observed 10 such opposite-sign dilepton events, where 6 were expected from \( \bar{t}t \) production with \( m_t = 175 \text{ GeV} \), and 2 events were expected from non-top Standard Model backgrounds [2, 3, 4].

Two of these events, which we label \( A \) and \( B \), have characteristics which are quite unlike those expected from \( \bar{t}t \) production. While this could result from a statistical fluctuation of the top signal, we present Monte Carlo distributions in Fig. 1 which illustrate how unlikely this is. The D0 collaboration has also observed dilepton events, one of which appears to have similar or even more dramatic characteristics [5].

The dashed curves in Fig. 1 show Monte Carlo distributions for dilepton events from \( \bar{t}t \) production for \( E_{T1}^\ell, E_T, E_S \) and \( \theta_T \). \( E_{T1}^\ell \) and \( E_{T2}^\ell \) are the transverse energies of the leading and subleading leptons, \( E_S = E_{T1}^\ell + E_{T2}^\ell + E_T \), and \( \theta_T \) is the angle between the the two isolated charged leptons in the plane transverse to the beam. The \( \theta_T \) distribution contains only events with \( E_S > 250 \text{ GeV} \).

Event \( A \) has values for \( E_{T1}^\ell, E_T \) and \( E_S \) which are on the tails of the distributions, see Fig. 1. This event contains a third isolated charged track, which is likely to be an electron. A third isolated, hard charged lepton would make this event inconsistent with a \( \bar{t}t \) origin. In event \( B \), the values for \( E_{T1}^\ell, E_T \) and \( E_S \) are again high, although the value for \( E_{T1}^\ell \) is not as large as in event \( A \). Fig. 1d shows that \( \bar{t}t \) production with high \( E_S \) leads to large values of \( \theta_T \). The measured values for \( \theta_T \) are both remarkably small, especially for event \( B \). A kinematic argument shows that the values of \( E_{T1}^\ell, E_{T2}^\ell \) and \( E_T \) of event \( B \) cannot arise from the decay of any pair of \( W \)'s whether or not the \( W \)'s originated in \( \bar{t}t \) production (neglecting neutrinos in the jets).

The central values of the variables \( E_{T1}^\ell, E_T \) and \( E_S \) for the D0 event, labelled \( C \), are far out on the tails of the distributions. However, the large uncertainty in the measurement of the muon \( E_T \) leads to large uncertainties in these variables. Although the event may be more dramatic than the CDF events, this uncertainty means that a \( \bar{t}t \) origin should not be excluded. We
believe that events A and B provide significant motivation for seeking an alternative origin for these dilepton events. Event C demonstrates that such exotic events may also be occurring in the D0 data.

The trademark of superpartner production at hadron colliders is well-known to be large $E_T$, signaling the escape of long-lived lightest superpartners (LSPs) produced in the decays of supersymmetric particles. It is also well-known that heavier squarks and gluinos tend to decay via a sequence of cascades through charginos ($\tilde{\chi}^\pm$) and neutralinos ($\tilde{\chi}^0$), yielding events with isolated charged leptons $\ell$ as well as jets and $E_T$ [6, 7]. The isolated charged leptons can arise from both $\tilde{\chi}^+, \tilde{\chi}^0$ decays, such as $\tilde{\chi}^+ \to \nu \bar{e}$, $\bar{e} \nu$ and $\tilde{\chi}^0 \to \bar{e} \bar{e}$, $\nu \nu$, and also from slepton decays, for example $\tilde{\nu} \to e \tilde{\chi}_1^0$. The lepton carries high $E_T$, provided there is a large mass difference between initial and final superpartners. In this letter we point out that, in the minimal supersymmetric extension of the Standard Model, there are plausible ranges of superpartner masses in which the cascade decays of squarks, $\tilde{q} \to \tilde{\chi} \to \tilde{\ell} \to \ell$, could lead to a few $\ell\ell jj E_T$ events, with extraordinarily high $E_T$ and $E_T^*$, in the last Tevatron run. Such an interpretation of the events A, B and C appears reasonable, but only if the squarks have a mass of about 310 GeV – beyond the reach previously thought possible for the Tevatron.

The minimal supersymmetric field content has two charginos and four neutralinos, so there are many options for the nature of the relevant $\tilde{\chi}$ states, which we call $\tilde{\chi}'$, and for the masses of the other $\tilde{\chi}$ states. However, in a 110 pb$^{-1}$ run few heavy squarks and gluinos are produced, so that the $\tilde{\chi}'$ states must have a high branching fraction to the desired leptonic mode. $\tilde{\chi}$ states lighter than $\tilde{\chi}'$ might deplete the signal by allowing decays $\tilde{\chi}' \to \chi H, \chi W$, where $H$ and $W$ are Higgs and gauge bosons of any charge. This suggests that the other $\chi$ states are heavier than the $\tilde{\chi}'$, which we find to have a mass of about 260 GeV, the exception being the lightest superpartner $\tilde{\chi}_1^0$, which should be dominantly bino. The bino does not couple to $W$ and its coupling to $H$ is proportional to the small hypercharge gauge coupling.

All charginos are at, or above, 260 GeV, so that the SU(2) gaugino mass parameter $M_2 \gtrsim 260$ GeV. The left-handed slepton mass receives radiative corrections from $M_2$, so that in all known models of supersymmetry breaking these sleptons are heavier than 150 GeV. The charged $\tilde{\chi}'$ are dominantly wino and therefore decay preferentially to left-handed sleptons. The typical
$E_T$ of the charged leptons from the cascade $\tilde{\chi}' \rightarrow \tilde{\ell}_L \ell$ is not as hard as the observed leading lepton in the collider events A, B and C. The most energetic leptons instead arise from slepton decay $\tilde{\ell}_L \rightarrow \tilde{\chi}_0^0 \ell$, so that the left-handed slepton mass must be large, in the region of 220 GeV. The lepton spectrum is hardened if the mass of $\tilde{\chi}_1^0$, the LSP, is small. This mass is given by the hypercharge gaugino mass parameter, $M_1$, which is therefore several times less than $M_2$. The region of parameters of interest to us does not allow the relation $M_2 \approx 2M_1$, which occurs in simple schemes of grand unification with large messenger scales for supersymmetry breaking.

What are the gaugino/higgsino components of the $\tilde{\chi}'$ states? If they were dominantly higgsino, they would be produced only in the decay of $\tilde{t}_R$, since other flavors of squarks would decay predominantly to the LSP bino, $q\tilde{\chi}_1^0$. To match the observed event rate would require a lower mass for $\tilde{t}_R$, and therefore of $\tilde{\chi}'$ and $\tilde{\ell}$, softening the $E_T^\ell$ and $E_T$ distributions. Furthermore, since the $\tilde{\chi}'$ states would decay to $\tilde{\ell}\ell$ only through their small wino components, this leptonic branching ratio would be depleted by the decay $\tilde{\chi}' \rightarrow H\tilde{\chi}_1^0$, at least for the neutral $\tilde{\chi}'$ states where the $H^0$ is guaranteed to be light. We conclude that the $\tilde{\chi}'$ states most likely have substantial gaugino components. In this letter we study the simplified case where there are three $\tilde{\chi}'$ states ($\tilde{\chi}$ states relevant to $\tilde{q}$ decays), and they are dominantly the $SU(2)_L$ gauginos: $\tilde{\chi}_1^\pm \approx \tilde{w}^\pm$ and $\tilde{\chi}_2^0 \approx \tilde{w}_3$. This is achieved by making the Higgsino mass parameter $|\mu| > 400$ GeV (for $M_2 = 260$ GeV). The heavier states $\tilde{\chi}_2^\pm$ and $\tilde{\chi}_{3,4}^0$ have masses near $|\mu|$ and play no role in our analysis. Similarly, the small Higgsino components of the $\tilde{\chi}'$ states are unimportant. We stress that while large $|\mu|$ was chosen for simplicity, the other aspects of the superpartner spectrum were dictated by the requirement of hard $E_T^\ell$ and $E_T$ distributions.

The requirement of hadron collider events with sufficiently hard $E_T^\ell$ and $E_T$ distributions has led us to a remarkably simple and plausible parameter region of the minimal extension of the supersymmetric standard model. There are five flavors of left-handed squarks with masses in the region of 310 GeV. These decay to $SU(2)_L$ gauginos, $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$, of mass near 260 GeV, which in turn decay to left-handed sleptons with mass near 220 GeV. The hardest charged leptons are produced in the final cascade of the sleptons to the LSP $\tilde{\chi}_1^0$, which is dominantly bino. With a squark mass as high as 310
GeV, it is remarkable that present collider data may contain a few events from this cascade: $\tilde{q}_L \rightarrow \tilde{\chi}_1^+; \tilde{\chi}_2^0 \rightarrow \ell_0 \rightarrow \ell \tilde{\chi}_1^0$.

The right-handed slepton masses are expected to be substantially smaller than the left-handed slepton masses because they do not receive the large radiative correction from $M_2$. This is fortunate since otherwise the LSP, $\tilde{\chi}_1^0$, would overclose the universe. Bino dark matter gives $\Omega h^2 = 0.5$, for $M_1 = 50$ GeV with three degenerate right-handed sleptons of mass $m_{\tilde{\ell}_R} = 130$ GeV.

The two top squarks, $\tilde{t}_{1,2}$, may be lighter or heavier than the other squarks. If heavier, they are rarely produced and are irrelevant. If lighter they can add to the hard lepton signature, by decaying to $\tilde{\chi}' q$, or to the dijet + $E_T$ signature by decaying to $t \tilde{\chi}_1^0$. We have not included such possible contributions in our analysis.

In our scheme, dilepton events, such as events $A$ and $B$, arise from the decay of a $\tilde{q}_L^{(\dagger)} \tilde{q}_L$ pair. Since $\tilde{g}$ decays to $q^\dagger \tilde{q}$ or to $qq^\dagger$, events from $\tilde{g} \tilde{q}$ and $\tilde{g} q^\dagger$ production (which can occur at a larger rate than $\tilde{q}^\dagger \tilde{q}$ events) look similar to $\tilde{q}^\dagger \tilde{q}$ events. Because $\tilde{q}_L$ has a small hypercharge, the direct decay $\tilde{q}_L \rightarrow q \tilde{\chi}_1^0$ has a small branching ratio compared to the cascade mode $\tilde{q}_L \rightarrow \tilde{\chi}_2^0, \tilde{\chi}_1^+ \rightarrow \ell \rightarrow \ell \tilde{\chi}_1^0$, even for our choices of masses ($m_{\tilde{q}_L} = 310$ GeV, $m_{\tilde{\chi}_1^+} = m_{\tilde{\chi}_2^0} = 260$ GeV) where the cascade mode is phase space suppressed. The predominant decay of each squark is therefore $\tilde{q}_L \rightarrow q(\tilde{\chi}_1^+; \tilde{\chi}_2^0)$, followed by $\tilde{\chi}_1^- \rightarrow \ell' \bar{\nu}^\dagger, \bar{\nu} \ell$ and $\tilde{\chi}_2^0 \rightarrow \ell' \bar{\nu}^\dagger, \nu \bar{\nu}^\dagger$, (together with the Hermitian conjugate decays), and finally $\ell \rightarrow \ell \tilde{\chi}_1^0$ and $\bar{\nu} \rightarrow \nu \tilde{\chi}_1^0$. The $E_T$ distribution for the $\ell'$, which appears in $\tilde{\chi}'$ decay, is softer than for the $\ell$, which appears in $\tilde{\ell}$ decay (for the masses we derive). These events therefore have a wide range of characteristics, with the number of isolated charged leptons, $N_L$, varying from 0 to 4, as shown in the Table.
Table

| N_L | \( \tilde{\chi}' \) charges | Charged leptons | Relative rate |
|-----|-------------------------------|-----------------|--------------|
| 0   | (0,0)                         |                 | 1            |
| 1   | (±,0)                         | \( \ell' \)     | 4            |
| 1   | (±,0)                         | \( \ell \)      | \( 4\rho \)  |
| 2   | (+,−) (±,±)                   | \( \ell' \ell' \)| 4            |
| 2   | (0,0) (+,−) (±,±)             | \( \ell' \ell \)| \( 10\rho \)  |
| 2   | (+,−) (±,±)                   | \( \ell \ell \) | \( 4\rho^2 \) |
| 3   | (±,0)                         | \( \ell' \ell' \ell \) | \( 4\rho \) |
| 3   | (±,0)                         | \( \ell' \ell \ell \) | \( 4\rho^2 \) |
| 4   | (0,0)                         | \( \ell' \ell' \ell \ell \) | \( \rho^2 \) |

The second column labels the charges of the two \( \tilde{\chi}' \) states produced from the two squark decays. The third column lists the possible combinations of the isolated leptons. Each \( \ell \) stands for e, \( \bar{e} \), \( \mu \), or \( \bar{\mu} \), which occur with equal probability. The flavors of different leptons are uncorrelated, except for those arising from \( \tilde{\chi}'_2^0 \to \ell' \ell\bar{\ell} \to \ell' \bar{\ell} \), when the flavors of the lepton and anti-lepton are identical. For simplicity we ignore the additional events with isolated charged leptons which can occur when one or both \( \tilde{\chi}' \) states decay to the \( \tau \) flavor.

The relative rates for the event categories are shown in the last column of the Table. The phase space factor \( \rho = (1 - m_{\tilde{\ell}}^2/M_2^2)^2(1 - m_{\tilde{\nu}}^2/M_2^2)^{-2} \) is less than unity since the \( D \) terms give \( m_{\tilde{\nu}} < m_{\tilde{\ell}} \). For \( \rho = 1 \), the Table shows that \( \frac{3}{4} \) of these \( q_L^{(1)} \bar{q}_L \) events have \( N_L \geq 2 \). Since the \( \ell' \) are typically soft, some care is necessary in interpreting these events. For example, the “mixed” dilepton events, \( \ell' \bar{\ell} \), typically have one very hard and one softer lepton, as observed for event A.

If some of the dilepton events at the Tevatron Collider have a supersymmetric origin, there is certainly an overlap region between these events and those from top quark decays. We have identified three events that seem very unlikely to originate from top decays. However, it is possible that there are other events whose characteristics are somewhat less dramatic but also come from squark decays.

Since each event would involve two separate squark decays, we can learn a little about the distributions by comparing the two lepton \( E_T \). Event A
may be instructive, since it contains both a 182 GeV lepton and a 27 GeV lepton. It is possible that one is at the high end of the distribution and the other at the low end.

With only three identified candidates for squark decays, it is not possible to quantitatively describe any distributions. Furthermore, the muon in event C (with $E_T \approx 200$ GeV) is not well-measured. Nonetheless it is possible to identify approximate masses of six supersymmetric particles within the assumed scenario. Given the small number of events, we will not give error bars on these masses, but estimate them as about $\pm (10 - 30)$ GeV.

The left-handed squark mass is determined to be about 310 GeV by the observed event rate, the production rate for $\tilde{q}_L^\dagger \tilde{q}_L$ and $\tilde{g} \tilde{q}_L^\dagger$, and the successive branching ratios, as discussed later. The squark decay $\tilde{q}_L \rightarrow q \tilde{\chi}'$ yields jets with $E_T \sim 20$-80 GeV though mostly at the low end. The implied $\tilde{q}_L - \tilde{\chi}'$ mass splitting gives $m(\tilde{\chi}_1^\pm) \sim m(\tilde{\chi}_2^0) \sim 260$ GeV.

In order to achieve the highest observed lepton $E_T$, it is essential that the sleptons have a very high mass and that $\tilde{\chi}_1^0$ not be too heavy. To be consistent with cosmology, and to maintain a large mass splitting with the sleptons, we take $m(\tilde{\chi}_1^0) \sim 50$ GeV. To obtain the hard lepton spectrum and not produce soft dilepton events (which are not seen in excess of the top quark events), the highest possible slepton mass is needed $m(\tilde{\ell}) \sim m(\tilde{\nu}) \sim 210$-230 GeV.

Having estimated the masses of $\tilde{q}$, $\tilde{\ell}$, $\tilde{\nu}$, $\tilde{\chi}_2^0$, $\tilde{\chi}_1^\pm$, and $\tilde{\chi}_1^0$, we plot several distributions in Fig. 1. Since these events all have $E_T^{\ell_1} + E_T^{\ell_2} + E_T$ well above 250 GeV, we use this cut in examining the transverse angle between the leptons (in Fig. 1d). Not shown but also interesting is the distribution of the slower lepton in the mixed mode which can yield softer leptons in one part of an event in some cases.

In our scheme, events A and B arise from cascade decays of $\tilde{q}_L^{(1)} \tilde{q}_L$. In a run of 110 pb$^{-1}$ the expected number of events with $N_L \geq 2$ is $(\sigma_T/0.05\text{ pb}) (\epsilon/0.25)$, where $\epsilon$ is the detection efficiency, which we estimate to be 0.25, and $\sigma_T$ is the total $\tilde{q}_L^{1\dagger} \tilde{q}_L + \tilde{q}_L \tilde{g} + \tilde{q}_L^{\dagger} \tilde{q}_L^{\dagger}$ production cross section. There are two contributions to $\sigma_T$ which may be important: direct $\tilde{q}_L^{\dagger} \tilde{q}_L$ production, and $\tilde{q}_L \tilde{g}$, $\tilde{q}_L^{\dagger} \tilde{g}$ production followed by $\tilde{g} \rightarrow \tilde{q}_L^\dagger \tilde{q}_L \tilde{q}_L^\dagger$. The relative importance of these two contributions depends on $m_\tilde{g}$ and $m_\tilde{q}_R$, which we have not deter-
Figure 1: Expected distributions for (a) $E_{T}^{\ell}$, (b) $E_{T}$, (c) $E_{T}^{\ell_{1}} + E_{T}^{\ell_{2}} + E_{T}$, and (d) $\theta_{T}$ (between the two leptons). The dashed curves are for $t\bar{t}$ production with $m_{t} = 175$ GeV. The curve labelled “mixed” has one lepton from $\tilde{\chi}' \rightarrow \ell \tilde{\nu}$ or $\ell \tilde{\ell}$ and one from $\tilde{\ell} \rightarrow \ell \tilde{\chi}^{0}_{1}$. The other solid curve has both leptons from $\tilde{\ell} \rightarrow \ell \tilde{\chi}^{0}_{1}$ decays. The three events mentioned in the text are labelled A, B, and C. Note that event A also has an isolated track that may be a third energetic lepton; this would increase the sum of $E_{T}$ for this event in (c). The $E_{T}$ of the muon in event C is very poorly measured; this uncertainty impacts on (a), (b), and (c).
For example, with \( m_{\tilde{g}} = 330 \text{ GeV} \) and \( m_{\tilde{q}_R} = m_{\tilde{q}_L} = 310 \text{ GeV} \), the direct production contributes 0.03 pb to \( \sigma_T \), while squark-gluino production contributes 0.07 pb to \( \sigma_T \). For these parameters, a further production rate, \( \sigma_B \), for dilepton events of 0.04 pb arises from \( \tilde{q}_L^{(t)}\tilde{q}_R^{(t)} \) production, giving a total expectation of about 3 events with \( N_L \geq 2 \). If \( \tilde{\tau}_L \) is degenerate with \( \tilde{e}_L \) and \( \tilde{\mu}_L \), this would be depleted by a factor of about 2.

For many years it has been proposed that a primary signature for supersymmetry would be events with leptons, jets, and missing energy. It was always clear that top quark decays would be a major background. We cannot demonstrate that the events we have studied are due to squark decays, but they appear not to come from top decays.

Perhaps the most notable result of our analysis is that with only three candidate events from a hadron collider, we are able to roughly estimate the masses of six supersymmetric particles (and the gaugino/Higgsino content of the \( \tilde{\chi}' \) states at 260 GeV). Clearly more data are needed to refine these estimates and to establish the particular scenario we have described.

The reported rate for dilepton events is about 30% higher than that expected from top quarks, but this excess is not statistically significant. If our scenario is correct, we also anticipate the observation of other types of events (though some may have significant backgrounds). As shown in the Table, we expect events with large missing \( E_T \) and 0, 1, 2, 3, and (very rarely) 4 leptons. These 1-lepton events may have only two jets and hence would not be in the top quark sample. The trilepton events are expected to contain jets, unlike those which would result from the production of much lighter chargino-neutralino pairs.

Additional signatures may also be present, depending on the values of \( m_{\tilde{q}_R} \) and \( m_{\tilde{g}} \). The production of \( \tilde{g}\tilde{g} \) contributes equally to same-sign and opposite-sign dileptons (\( \tilde{q}^{(t)}\tilde{q} \) production can also lead to same-sign events). When right-handed squarks are produced, they decay directly to the LSP: \( \tilde{q}_R \rightarrow q_R \tilde{\chi}_1^0 \), so that several new signals are possible. For example, with \( m_{\tilde{g}} = 330 \text{ GeV} \) and \( m_{\tilde{q}_R} = m_{\tilde{q}_L} = 310 \text{ GeV} \), we find a production rate, \( \sigma_B \), for \( (jj E_T, jj\ell E_T) \) events of \( (0.15, 0.19) \) pb. The standard model backgrounds for these \( N_L = 0, 1 \) events are larger than for the case of \( N_L = 2 \). However,

\[ \text{We do not assume the universality relation } m_{\tilde{q}_R} = m_{\tilde{q}_L}, \text{ nor do we exclude it.} \]
the signal events are prominent: the \(jj E_T\) events have \(E_T^j \sim 50 - 230\) GeV and \(E_T \sim 50 - 280\) GeV. For values of \(|\mu|\) below 400 GeV, the decays of charginos to \(W^+\tilde{\chi}^0_1\), \(H^+\tilde{\chi}^0_1\) and neutralinos to \(Z\tilde{\chi}^0_1\), \(H^0\tilde{\chi}^0_1\) may become important.

Remarkably we find that the Tevatron Collider experiments can be sensitive to very high squark masses, in excess of 300 GeV. In our scenario this happens because the relevant charginos and neutralinos have masses between the squarks and the sleptons, leading to high leptonic branching ratios and to hard \(E_T^\ell\) and \(E_T\) distributions. The reach in squark mass exceeds that of several previous analyses, because the signal can be distinguished from the \(\bar{t}t\) background. Without such a kinematic distinction, the signal can only be seen with large statistics, leading to a more limited reach in the squark mass. The superpartner masses of our scheme are so high that no supersymmetric particle would be found at LEP2, and a 500 GeV NLC would not find all of these particles. If this turns out to be the first evidence for supersymmetry, the confirmation will come in the next Tevatron run which may obtain 10-20 times as many events. It may also be possible to identify a few events with large \(E_T\) and 0, 1, 2 same-sign, or three isolated leptons in the present data.

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