Do About Half the Top Quarks at Fermilab Come from Gluino Decays?

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We argue that it is possible to make a consistent picture of Fermilab data including the production and decay of gluinos and squarks. Assuming the stop squark mass is small enough, about half of the top quarks decay to stop squarks, and the loss of standard model top quark pair production rate is compensated by the supersymmetric processes. This behavior is consistent with the reported top quark decay data and suggests several other possible decay signatures. This picture can be tested easily with more data, perhaps even with the data in hand. It also has implications for the top mass measurement and the interpretation of the CERN e^+e^- collider LEP R_b excess. [S0031-9007(96)01485-8]

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While there is still no unambiguous experimental evidence that nature is supersymmetric on the weak scale, there have been recent reports of data that encourage this view. The most explicit is an event in the Collider Detector at Fermilab (CDF) [1] that does not have a probable standard model (SM) interpretation, and can naturally be explained as selectron pair production [2,3]. In the interpretation when the lightest neutralino is the lightest superpartner (LSP) [2], which is the focus of this Letter, the analysis of this event leads to a fairly well determined range of masses and couplings for sleptons $\tilde{\ell}$, charginos $\tilde{C}_i$, and neutralinos $\tilde{N}_i$. $\tilde{C}_i$ and $\tilde{N}_i$ are the chargino and neutralino mass eigenstates, with $\tilde{C}_1, \tilde{N}_1$ ($\tilde{C}_2, \tilde{N}_4$) being the lightest (heaviest) chargino and neutralino. Such masses suggest (but do not require) gluino and squark masses in the range 200–300 GeV. If in addition there is a stop squark $\tilde{t}$ lighter than about the Z boson mass M_Z, it is remarkable that the chargino mass and couplings from [2] can explain [4] the LEP reported excess for $Z \longrightarrow b\bar{b}$ decays (R_b), at least if that excess is not too large. The δR_b value recently presented at Warsaw ($\delta R_b = 0.0018 \pm 0.0011$) is more compatible with this scenario than previous larger values, and implies a shift in the strong coupling α_s at M_Z, $\delta\alpha_s \simeq 4\delta R_b$. It is still an open question whether $\alpha_s(M_Z)$ is compatible with the SM ($\alpha_s \simeq 0.120$) or is lower ($\alpha_s \lesssim 0.116$) as expected when there is a light stop, and this answer depends critically on several physics assumptions. When one also considers that these masses and couplings explain the observed branching ratio $B(b \longrightarrow s\gamma)$, this picture becomes more compelling. At present [6] R_b and $B(b \longrightarrow s\gamma)$ differ from their SM predictions by 1.5-2σ, and α_s measured by the Z width differs by about 1.5-2σ from its value measured in deep-inelastic scattering (DIS) and other ways. Another encouraging result [7] is that the LSP resulting from these studies is a good candidate for the cold dark matter of the universe, giving $0.1 \lesssim \Omega_{\rm LSP}h^2 \lesssim 1$, where $\Omega_{\rm LSP}$ is the relative density of LSP matter in the universe and h is the Hubble constant. In the following, we use the $\tilde{N}_i$ and $\tilde{C}_i$ masses and couplings reported in Ref. [2], giving a $\tilde{N}_1$ LSP that is mostly higgsino ($\tilde{h}$).

In this Letter we observe that supersymmetry (SUSY), with certain reasonable and well-motivated choices of sparticle masses, will lead to extra $t\bar{t}$ production. Additionally, there are other final states from sparticles with a high purity of b-quarks, leptons, and jets which can mimic the $t\bar{t}$ signal. We use the term minimal supersymmetric SM (MSSM) to describe our models. We do not assume gaugino mass unification or impose any fixed relations between gaugino or scalar masses. In our models, the stop squark $\tilde{t}$ and at least one neutralino $\tilde{N}_i$ are light, and the top quark decay $t \longrightarrow \tilde{t}\tilde{N}_i$ must occur along with $t \longrightarrow bW$. This branching ratio is about $1/2$ when $\tilde{N}_i$ is $\tilde{h}$-like, since the coupling of t to $\tilde{h}$ and the longitudinal W boson are both proportional to the top mass m_t. If half of the top quarks decay to stop squarks, then $\bar{t}(\longrightarrow \bar{b}W)t(\longrightarrow \tilde{t}\tilde{N}_i)$ followed by $\tilde{t} \longrightarrow c\tilde{N}_j$ [9], so half of all $t\bar{t}$ events give a Wbc signature. This process is Cabibbo suppressed in the SM, and gives a rate less than $1/9$–$1/5$ of that in our explicit MSSM models. Similar observable differences occur in every distinct $t\bar{t}$ channel; this is demonstrated later. Furthermore, a different value of m_t is likely to be extracted from different channels if it is determined by comparison with a SM Monte Carlo, and the true value of m_t might not be the apparent one. Note that a large number of charm jets arise from stop decays; if they could be tagged, e.g., by the lepton in charm semileptonic decays, it would help test our arguments.

The Fermilab experiments report essentially two independent measures of m_t: the kinematic measure, based on reconstructing the t four-momentum, and the counting measure, based on the number of observed events. Given the measured quantities from CDF and D0 [10,18] of m_t and $\sigma_{t\bar{t}} \times b_W^2$ and the theoretical predictions and their uncertainties, a χ^2 minimization yields $m_t = 168.6^{+3.0}_{-3.0}$ GeV,

$\sigma_{t\bar{t}} = 7.09^{+0.68}_{-0.62}$ pb, and $b_W = 1.00^{+0.00}_{-0.13}$. At the 95% confidence level, $b_W \geq 0.74$, so there is an upper limit on $B(t \to X)$, where $X \neq bW$, of about 25% [11]. While this analysis disfavors a large component of non-SM top quark decays, such as a $\tilde{t} \longrightarrow c\tilde{N}_1$, it has limitations. It does not include the possibility that the physics which allows new top quark decays can also lead to more top quark production. [See [12] for an analysis which includes $\tilde{t}\tilde{t}^*$ production and the decays $\tilde{t} \longrightarrow b\tilde{C}_1$ and concludes that a light $\tilde{t}$ is not excluded by the present Fermilab data even for $B(t \longrightarrow \tilde{t}\tilde{N}_i) = 1/2$]. It assumes that all of the new decay modes result in final states which elude the standard searches. Finally, it does not include the LEP indirect fits to m_t which favor a lower value (for example, the world average top mass including LEP, DIS, SLC, and Fermilab data is 161 ± 8 GeV, assuming an 80 GeV Higgs boson, as expected from Ref. [4]), which would increase $\sigma_{t\bar{t}}$ and lower b_W. Based on these observations, it is premature to conclude that a light stop is inconsistent with the observed top quark events. In the following, we present explicit supersymmetric models motivated by Ref. [2] which elude the above $B(t \longrightarrow X)$ limit.

If selectrons, charginos, and neutralinos have masses of order M_Z, then squarks ($\tilde{q}$) and gluinos ($\tilde{g}$) might be light enough to be produced in significant numbers at Fermilab. The analysis of Ref. [2] is done with a general low energy softly broken SUSY theory, without assumptions about gaugino or squark mass unification. As a result, the gluino and squark masses $m_{\tilde{g}}$ and $m_{\tilde{q}}$ are not determined. However, there are phenomenological reasons to settle on the range 200–300 GeV for these masses. Given the analysis of R_b and $B(b \longrightarrow s\gamma)$, we expect $m_{\tilde{t}} \lesssim M_Z$. LEP and Fermilab limits do not allow $m_{\tilde{t}}$ to be too small [13], and we are led to 45 GeV $\lesssim m_{\tilde{t}} \lesssim M_Z$. Light stop squarks alone dilute the signal $t \longrightarrow bW$ through decays $t \longrightarrow \tilde{t}\tilde{N}_i$ at a level incompatible with the data, so a new top quark or toplike production mechanism is needed. The gluino will decay [14] $\tilde{g} \longrightarrow t\tilde{t}^*$ or [15] $\tilde{g} \longrightarrow \overline{t}\tilde{t}$ if $m_{\tilde{g}} > m_t + m_{\tilde{t}}$. If $m_{\tilde{q}} > m_{\tilde{g}} + m_q$, then $\tilde{q} \longrightarrow \tilde{g}q$. Finally, since about half of the top quark decays "disappear", we need a production mechanism which is about the same size as the SM rate. Therefore, we are naturally led to squark and gluinos masses of 200–300 GeV. If these masses are much heavier, then the production cross section at the Tevatron becomes too small to affect the top signal. This is consistent if $m_{\tilde{t}}$ is heavier than M_Z, since $B(t \longrightarrow \tilde{t}\tilde{N}_i)$ is suppressed and the decay $t \longrightarrow bW$ is not depleted, but then we must treat as irrelevant the pieces of data suggesting a light stop. We will see that a number of observables depend on the particular masses, so eventually they can be directly measured. This range for $m_{\tilde{q}}, m_{\tilde{g}}$ is not excluded by other SUSY searches.

A similar mass hierarchy follows from theoretical considerations. Reference [2] found U(1) and SU(2) gaugino masses obeying the mass relations $M_1 \simeq M_2$, rather than the unification relation $M_1 \simeq \frac{1}{2}M_2$. This could be explained by anomalous behavior of the U(1) mass, so that the SU(2) and SU(3) masses may still approximately satisfy the unification relation $M_2 \simeq \frac{1}{3}M_3$. Then $m_{\tilde{g}} \simeq 3m_{\tilde{C}_1}$, or in the range 195–270 GeV. Similarly, models suggest that left- and right-hand squark masses (except for $\tilde{t}$) are approximately degenerate and about 2.5 times the selectron mass. For numerical work, we use a common $m_{\tilde{q}}$ (except for $\tilde{t}$) which is slightly above $m_{\tilde{g}}$. We study models with $160 < m_t < 175$ GeV, $210 < m_{\tilde{g}} < 235$ GeV, $220 < m_{\tilde{q}} < 250$ GeV, and $45 < m_{\tilde{t}} < 60$ GeV. All results are based on the analyses and models of Refs. [2,4] and are thus consistent with existing evidence for SUSY and with other particle physics constraints, including all LEP new particle searches to date. In general, the models of Refs. [2,4] have a higgsino mass $\mu < 0$, $|\mu| \lesssim M_1 \simeq M_2 \simeq M_Z, \tan\beta \lesssim 2$, and $m_{\tilde{\ell}} \simeq 100$ GeV, and predict a fairly light $\tilde{C}_i, \tilde{N}_i$ spectrum. In particular, the LEP upgrades are sensitive to $\tilde{C}_1^+\tilde{C}_1^-$ (with a W^+W^- background) and $\tilde{N}_1\tilde{N}_3$ production, provided the $\tilde{N}_3$ decays are visible. Furthermore, the lightest Higgs boson mass resulting from these parameters is not excluded by LEP data. See the references for more details.

Here, we present separate results on the counting measurement of the top production cross section and kinematic measurement of the top quark mass in the SUSY models described in the previous section. All event simulation is performed using the Monte Carlo PYTHIA 5.7 with supersymmetric extensions [16] and a simple calorimeter simulation. To eliminate dependence on the particulars of b tagging and isolation efficiencies and detector cracks, we present results as ratios with the expected SM signal from the top quark search modes defined by the CDF cuts [17]: (i) leptonic, (ii) dileptonic, and (iii) hadronic. We find substantial signals in two additional channels: (iv) Wbc, and (v) γbc. The channel (iv) cuts are the same as for (i), except only two jets are allowed. The excess number of Wbc events (where W may have a different transverse mass since $\tilde{N}_1$'s carry away energy) would appear as an excess of W plus two jet events with one b tag; the second jet is charm which can be tagged with a lower efficiency. The channel (v) cuts require a high-p_t γ (>20 GeV) in the central rapidity region ($|\eta^\gamma| < 1$), with two or more additional jets. One of the two leading jets must have a b tag. The SM contribution to channel (iv) should be limited; using the same level of event simulation, we estimate the SM rate is less 40 fb. Channel (v) events arise from the decay $\tilde{N}_2 \longrightarrow \tilde{N}_1\gamma$ in association with top quark or toplike decays, and should have a tiny contribution from $t\bar{t}$ production alone in the SM.

Table I summarizes the results of the counting experiments for the various models considered. In the upper portion of the table, we present the ratio of the MSSM rate and SM $t\bar{t}$ rate after cuts. These numbers suggest that different values will be obtained for the $t\bar{t}$ cross section in different modes; in a given mode, the value will depend on the analysis and cuts. This is consistent with the reported CDF and D0 cross

TABLE I. Expected results of the top quark counting experiments for the MSSM. The apparent top production cross sections are shown in the final column. The number of events in the present data sample for two channels are displayed in the middle section. Typical MSSM production cross sections appear in the final section. The smaller contributions from $\tilde{g}\tilde{g}$ and $\tilde{q}\chi$ are not listed separately, but appear in the sum.

Mode	MSSM $t\bar{t}$	$\tilde{q}\tilde{q}$	$\tilde{q}\tilde{g}$	MSSM sum	"$\sigma_{t\bar{t}}$"
Ratio with expected SM cross section					
$\ell^{\pm}n_j \geq 3$	0.35–0.43	0.07–0.10	0.13–0.19	0.71–0.74	3.9–6.5
$\ell^{\pm}\ell^{\mp}$	0.31–0.38	0.10–0.21	0.08–0.18	0.58–0.87	3.8–7.8
$\ell^{\pm}\ell^{\pm}$	0.03–0.04	0.02–0.04	0.02–0.03	0.10–0.14	
$n_j \geq 6$	0.28–0.35	0.10–0.16	0.20–0.23	0.66–0.86	4.3–6.5
Number of events in 100 pb $^{-1}$					
$\ell^{\pm}n_j = 2$	13–19	0–2	1–5	17–33	
γbj	7–13	6–22	6–23	26–69 + 35	
Production cross sections					
σ (pb)	5.5–9.0	1.7–4.1	1.9–5.2	10.7–21.6	

sections [18], certainly as consistent as assuming the different mean values in each mode will settle on the SM value with more statistics. The row labelled $\ell^{\pm}\ell^{\pm}$ shows the predicted non-SM signal of like sign leptons; this is possible because of the Majorana nature of the gluino. About $1/7$–$1/5$ of all dilepton events should have leptons with the same charge. The middle section of the table shows the expected number of events in 100 pb^{-1} for the two aforementioned channels Wbc and γbj. These numbers do not include a b-tagging efficiency. Also included in the γbj sample is the expected number of events from $\tilde{C}_i(\longrightarrow b\tilde{t})\tilde{N}_2(\longrightarrow \tilde{N}_1\gamma)$ production (+35). The final section shows the variation in total production cross sections for the various channels. Note that the MSSM $t\bar{t}$ production cross section is identical to the SM one; the only difference occurs in the allowed top quark decays. Of course, the various apparent cross sections are correlated. For $m_t = 160$ GeV, $m_{\tilde{q}} = 220$ GeV, $m_{\tilde{g}} = 210$ GeV, $m_{\tilde{N}_1} = 38$ GeV, $m_{\tilde{t}_1} = 45$ GeV, the cross sections measured in the three modes are 6.5, 7.8, and 6.6 pb. For $m_t = 165$ GeV, $m_{\tilde{q}} = 240$ GeV, $m_{\tilde{g}} = 220$ GeV, $m_{\tilde{N}_1} = 38$ GeV, $m_{\tilde{t}_1} = 50$ GeV, the numbers are 5.7, 5.3, and 6.3 pb.

Some of the larger apparent rate for $t\bar{t}$ production for SUSY processes comes from the increased cross section for smaller m_t. We use the resummed $t\bar{t}$ prediction of Ref. [8]. The production of squarks and gluinos is calculated only in lowest-order QCD and could receive a substantial correction [19], which we have not included. In addition, smaller m_t allows for smaller gluino and squark masses, which further increases the MSSM rate. We have made no attempt to optimize the numbers in Table I. It is remarkable how naturally the apparent cross section values span the experimentally allowed values.

Since they are a novel feature of our models, we also show a typical scatter plot of the events expected in 100 pb^{-1} with signature $\gamma b \not{E}_T$ + jets in Fig. 1, resulting from models with $m_t = 160$ GeV. There is no parton-level SM source of such events, and our MSSM scenario predicts a significant number. Figure 1 is a scatter plot of the bj invariant mass (M_{bj}) versus the γbj mass ($M_{\gamma bj}$), with j the leading jet. There are three sources of these events, each denoted by different symbols in the figure: $q\overline{q} \longrightarrow \tilde{C}_i(\longrightarrow b\tilde{t}^*)\tilde{N}_2(\longrightarrow \gamma\tilde{N}_1)$, $q\overline{q}(gg) \longrightarrow t[\longrightarrow bW(\longrightarrow jj)]\bar{t}[\longrightarrow \tilde{t}^*\tilde{N}_2(\longrightarrow \gamma\tilde{N}_1)]$, with $\tilde{t} \longrightarrow c\tilde{N}_1$, and cascade decays from $\tilde{q}\tilde{q}$, $\tilde{q}\tilde{g}$, $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{N}_i$, $\tilde{g}\tilde{C}_i$, $\tilde{q}\tilde{N}_i$, $\tilde{q}\tilde{C}_i$, populating different regions of the plot. The $\tilde{C}_i\tilde{N}_2$ and $t\bar{t}$ signals depend mostly on the SUSY interpretation of the CDF event and the postulate of a light stop squark; their signal may be present regardless of the other squark and gluino processes. Note that the first of these produces only two prompt jets, while the other two produce several jets. Finding these events could confirm supersymmetry in general and our arguments in particular.

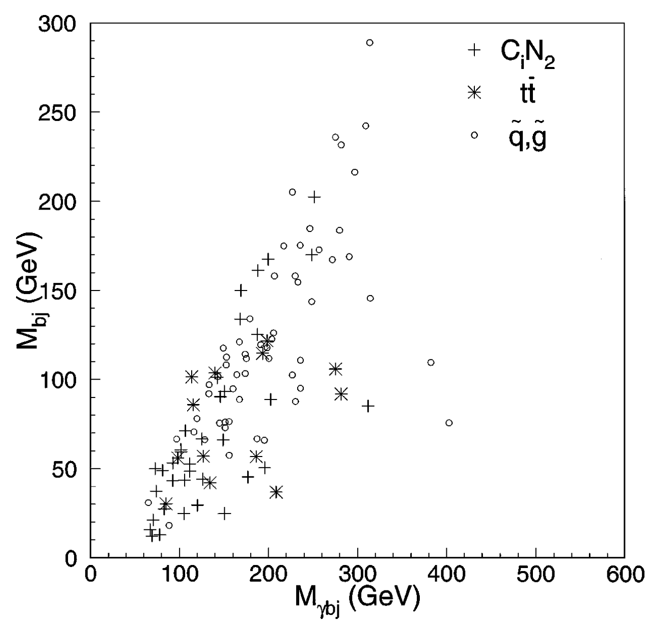

FIG. 1. The distribution of γbj events expected in 100 pb^{-1}. There are contributions from the $\tilde{C}_i\tilde{N}_2$, $t\bar{t}$, and $\tilde{q}, \tilde{g}$ production processes. The cuts are described in the text. There is no parton-level SM background for these events.

In addition to the top quark measurements based on counting events, there are kinematic measurements. While we have performed only a crude simulation, we find that the $t\bar{t}$ invariant mass and transverse momentum distributions in our MSSM are consistent with the data.This consistency is understandable. Since some top quarks are coming from gluino decay ($\tilde{g}\tilde{g} \longrightarrow t\bar{t}\bar{\tilde{t}}\tilde{t}^*$) just above threshold, they are produced almost at rest in the lab frame. As a result, the distribution must peak slightly above $2m_t$. The additional jets and $\not{E}_T$ from $\tilde{t}$ decays, for example, are less important than experimental resolution and the effects of initial state radiation. The MSSM transverse momentum of the $t\bar{t}$ pair is significantly broader than that expected in the SM. Using the same example of $\tilde{g}\tilde{g} \longrightarrow t\bar{t}\bar{\tilde{t}}\tilde{t}^*$, there is no reason to expect that the t and $\bar{t}$ momenta will approximately balance in p_T as expected from SM $t\bar{t}$ production. The SM $t\bar{t}$ distribution displayed in Ref. [20] is considerably narrower than the data, so the MSSM could explain this discrepancy.

The events used for the kinematic reconstruction of m_t with a b tag come from the $W(\longrightarrow \ell\nu)$ + jets mode. The lepton and the $\not{E}_T$ in these events should have a transverse mass consistent with that from the decay of a W boson. When top quarks are produced in MSSM events, there can be additional $\not{E}_T$ from cascade decays down to $\tilde{N}_1$. We have compared the expected distributions for the transverse mass in the MSSM and the CDF data [21]. While the MSSM distribution is indeed somewhat wider, the present date is easily consistent with both.

Since many of the apparent top events have extra associated jets, the apparent top mass deduced from such events will only be the actual top mass if very particular cuts and analyses are used. This is obvious, since the CDF and D0 kinematic analyses rely extensively on Monte Carlo of SM $t\bar{t}$ events to define jets and correct jet energies. We have found one measure of this effect which does not depend on the details of the event reconstruction: the invariant mass distribution of the leptons in dilepton events is softer than for SM top events. This indicates that the mass kinematically reconstructed from dilepton events will be lower in the MSSM than for the other modes. Note that this is the only mode which does not require a b tag, so that the additional jets from squark decays can enhance the signal.

We have argued that existing data is consistent with the possibility that hundreds of squarks and gluinos have been produced at Fermilab. Squarks decay mainly into gluinos, charginos, and neutralinos, gluinos into top quarks and stop squarks, and $B(t \longrightarrow \tilde{t}\tilde{N}_i)$ is about $1/2$. We have checked that the predicted counting measures and kinematic measures are consistent with the available data, and, in some cases, give a better description. A number of associated predictions allow this view to be tested, possibly with existing data. If correct, it has implications for the top quark mass and cross section measurements, for interpreting the LEP R_b data, the value of α_s, and $B(b \longrightarrow s\gamma)$, and of course for the existence of supersymmetry in nature.

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