Do About Half the Top Quarks at FNAL Come From Gluino Decays?

G. L. Kane

Randall Laboratory of Physics
University of Michigan
Ann Arbor, MI 48104

and

S. Mrenna

High Energy Physics Division
Argonne National Laboratory
Argonne, IL 60439

Abstract

We argue that it is possible to make a consistent picture of FNAL data including the production and decay of gluinos and squarks. The additional cross section is several pb, about the size of that for Standard Model (SM) top quark pair production. If the stop squark mass is small enough, about half of the top quarks decay to stop squarks, and the loss of SM top quark pair production rate is compensated by the supersymmetric processes. This behavior is consistent with the reported top quark decay rates in various modes and other aspects of the data, and suggests several other possible decay signatures. This picture can be tested easily with more data, perhaps even with the data in hand, and demonstrates the potential power of a hadron collider to determine supersymmetric parameters. It also has implications for the top mass measurement and the interpretation of the LEP $R_b$ excess.

PAC codes: 12.60.Jv, 12.15.Mm, 14.65.Ha, 14.80.L
1 Introduction

While there is still no compelling 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 CDF [1] that does not have a probable SM interpretation, and can naturally be explained as selectron pair production [2, 3]. In the interpretation when the lightest neutralino is the LSP, the analysis of this event leads to a fairly well determined range of masses and couplings for sleptons $\tilde{\ell}$, charginos $C_i$, and neutralinos $N_i$. $C_i$ and $N_i$ are the chargino and neutralino mass eigenstates, with $C_1, N_1$ ($C_2, N_4$) being the lightest (heaviest) chargino and neutralino. If in addition there is a light stop squark $\tilde{t}$ (i.e., $m_{\tilde{t}} \lesssim m_W$), it is remarkable that the chargino mass and couplings from [2] can explain [4] the LEP reported excess for $Z \rightarrow b\bar{b}$ decays ($R_b$), at least if that excess is not too large. Another encouraging result [6] is that the LSP resulting from these studies has a mass and coupling such that it is a good candidate for the cold dark matter of the universe, giving $0.1 \lesssim \Omega_{\text{LSP}} h^2 \lesssim 1$. In the following, we use the $N_i$ and $C_i$ masses and couplings reported in Ref. [2].

If the stop squark $\tilde{t}$ and at least one neutralino $N_i$ are light, the top quark decay $t \rightarrow \tilde{t}N_i$ must occur along with $t \rightarrow bW$ with branching ratio about one–half. Currently, the FNAL top quark pair production counting rate is interpreted as a measurement of $\sigma(p\bar{p} \rightarrow t\bar{t}X) \times \text{BR}(t \rightarrow bW)$. The reported values from CDF for this are about 7 pb [14], which is already larger than the predicted total cross section [7] (about 5.5 pb) for the top quark mass ($m_t$) extracted from kinematic reconstruction (about 175 GeV). The D0 measurement for the production rate is smaller, but suffers from larger backgrounds. Unless there is additional production of top quarks or other particles with similar decay modes, there is no room for extra decay modes, such as $t \rightarrow \tilde{t}N_i$, in this data sample (this is made quantitative below).

In this paper we observe that supersymmetry, with certain reasonable and well–motivated choices of sparticle masses, will lead to extra top quark production. Additionally, there are other final states from sparticles with a high purity of $b$–quarks, leptons, and jets; they can mimic the top quark signal. If squark ($\tilde{q}$) and gluino ($\tilde{g}$) masses (excepting the stop squark) are between 200 and 300 GeV, then they have pb–level production rates at the Tevatron. We assume squarks are heavier than gluinos, motivated by the results of Ref. [2] as well.
as the observation that gluinos decay predominantly to top quarks and stop squarks if the
decays to other squarks are not kinematically allowed. A lower bound is set for the gluino
mass by requiring $m_{\tilde{g}} > m_t + m_\tilde{t}$ so that the decay $\tilde{g} \rightarrow t\tilde{t}^*$ can occur for physical masses.
Since gluinos are Majorana particles, they will decay equally to $t\tilde{t}^*$ and $\tilde{t}t$.
Pair production of $\tilde{g}\tilde{g}$ will give a final state containing $tt, \tilde{t}\tilde{t}$, and $t\tilde{t}$ in the ratio $1 : 1 : 2$. If squarks
are heavier than gluinos, they decay as $\tilde{q} \rightarrow \tilde{g}q, C_iq, N_iq$; $\tilde{g}q$ has the largest coupling but
the smallest phase space. We assume that $R$-parity is approximately conserved, as implied
by the interpretation of the CDF event as sparticle production, so that all sparticles decay
to $N_1$ within the detector, and $N_1$ subsequently escapes. The couplings to $C_i$ and $N_i$ are
largely determined by the analysis of Ref. [2]. The size of the BR($\tilde{q} \rightarrow \tilde{g}q$) is determined
by the available phase space. We freely use the term Minimal Supersymmetric Standard
Model (MSSM) to describe our models, and it should be understood that we do not assume
gaugino mass unification, but we do assume that all squarks except the stop squark are
mass degenerate.

The relative masses of $\tilde{t}$ and $C_i$ are important for the signatures, and are not determined
yet. Motivated by the LEP $R_b$ data, we assume $m_{\tilde{t}} \lesssim m_{C_i}$. Then the dominant decays
are $C_i \rightarrow b\tilde{t}^*$, and $\tilde{t} \rightarrow cN_i$. If half of the top quarks decay to stop squarks, then
$\tilde{t}(\rightarrow bW)t(\rightarrow \tilde{t}N_i)$ followed by $\tilde{t} \rightarrow cN_j$, so half of all $t\tilde{t}$ events give a $Wbc$ signature; the
finite detector acceptance, clustering of jets, etc., might lead to a similar final state in the
Standard Model, but at a much lower rate. Similar observable differences occur in every
distinct $t\bar{t}$ channel; results for some examples are shown in Sec. 4. 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 semi-leptonic decays, it would help test our arguments.

In the following section, we review several results on the top quark which are relevant to
our discussion. In Section 3, we present a supersymmetric model which is consistent with
the results of Section 2, explains several other pieces of data, and predicts several signatures
in the present and future FNAL data samples. The detailed study of these models are shown
in Section 4. Finally, Section 5 contains our conclusions.
2 Upper Bound on Non–SM Decay Modes of The Top Quark

Based on a number of measurements and predictions, it is possible to bound non–SM decay modes of the top quark which are “invisible” to the standard searches. The final state resulting from \( t\bar{t} \to bWcN_1N_1 \) or \( t\bar{t} \to cN_1cN_1N_1N_1 \) would not have enough leptons or jets to be included in the leptonic, dileptonic, or hadronic event samples, and, hence, is invisible. Here, we review briefly a previous analysis bounding these “invisible” decays\[10\].

The FNAL experiments report essentially two independent measures of the top quark mass: the kinematic measure, whereby the four–vectors of all the decay products are reconstructed into the four–vector of the parent particle, and the counting measure, whereby one compares the observed number of events, corrected by efficiencies, to the production cross section as a function of mass. Additionally, based on single– and double–b–tagged events, CDF has reported a measurement of \( \text{BR}(t \to qW) \) for \( q \neq b \). \[11\]. We interpret this as a limit on \( bW \equiv \text{BR}(t \to bW) \). The SM prediction for the production cross section \( \sigma_t \) is bounded theoretically and the current best prediction of \( \sigma_t \) at \( m_t = 175 \) GeV is \( 5.52^{+0.07}_{-0.45} \) pb from the first reference of \[7\]. Given the measured quantities and the theoretical predictions and their uncertainties, one can perform a \( \chi^2 \) minimization in the variables \( m_t, \sigma_t, \) and \( bW \). Finding the minimum value \( \chi^2_{\text{min}} \) yields \( m_t = 168.6^{+3.0}_{-3.0} \) GeV, \( \sigma_t = 7.09^{+68}_{-62} \) pb and \( bW = 1.00^{+0.00}_{-0.13} \). At the 95% confidence level, \( bW \geq 0.74 \), so an upper limit on \( \text{BR}(t \to X) \), where \( X \neq bW \), exists of about 25%.

This analysis disfavors a large component of non–SM top quark decays, such as \( \tilde{t} \to cN_1 \). However, this result has limitations. Namely, it does not include the possibility that the same physics which allows new top quark decays can also lead to more top quark production. (See \[12\] for an analysis which includes \( t\bar{t}^* \) production and the decays \( \tilde{t} \to bC_1 \) and concludes that a light \( \tilde{t} \) is not excluded by the present FNAL data even for \( \text{BR}(t \to \tilde{t}N_i)=1/2 \). Furthermore, 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 FNAL data is \( 161\pm8 \) GeV assuming an 80 GeV Higgs boson, as expected from Ref. \[4\]). Since this would weight the \( \chi^2 \) for a smaller \( m_t \) and a larger \( \sigma_t, bW \) would be smaller. and more “invisible” decays would be allowed. Based on these observations, it is premature to conclude that a light stop is inconsistent with the observed top quark events. In the
following section, we present explicit supersymmetric models motivated by Ref. [2] which successfully address several of the loopholes in the previous analysis. Squarks and gluinos are produced at a significant rate and decay largely into top quarks. The stop squark is light enough that the charginos $C_1$ and $C_2$ decay to $b\tilde{\tau}^*$, which in combination with other decays, give top-like final states. Finally, a lower top mass predicts a larger SM production rate, allowing more “invisible” decays.

3 Top Quarks from Squark and Gluino Decay

If selectrons, charginos, and neutralinos have masses of order $m_Z$, then squarks and gluinos might be light enough to be produced in significant numbers at FNAL. The analysis of Ref. [2] is done with a general low energy softly broken supersymmetry theory, without assumptions about gaugino or squark mass unification. As a result, the gluino and squark masses are not determined. However, there are phenomenological reasons to settle on the range 200–300 GeV for these masses. Given the analysis of $R_b$, we expect a light stop squark with mass less than about $M_W$. LEP and FNAL limits do not allow this to be too small [13], and we are forced to $m_{\tilde{t}}$ values somewhere between about $M_Z/2$ and $M_W$. As explained in the previous section, light stop squarks alone dilute the signal $t \to bW$ through decays $t \to \tilde{t}N_i$ at a level incompatible with the data, so a new top quark or top-like production mechanism is needed. The simplest method is to use the decay channel $\tilde{g} \to \tilde{t}\tilde{\tau}^*$, which requires $m_{\tilde{g}} > m_t + m_{\tilde{t}}$. For this to be the dominant decay channel, the other squarks must be heavier than the gluino. Finally, the Tevatron has limited parton luminosities to produce heavy particles. 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 lead to squark and gluinos masses between 200 and 300 GeV. We will see that a number of observables depend on the particular masses, so eventually they can be directly measured.

A similar mass hierarchy follows from theoretical considerations. Ref. [2] found 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 non-Abelian masses may still approximately satisfy the unification relation $M_2 \simeq M_3$. Then the gluino mass should be about three times the $C_1$ mass, or in the range 195–270 GeV. Similarly,
we assume here that squarks are (except for stop mass eigenstates that are expected to be separated) approximately degenerate, and about 2.5 times the selectron mass, as suggested by models. For numerical work, we take a common squark mass $m_{\tilde{q}}$ for left- and right-handed squarks of five families which is slightly above $m_{\tilde{g}}$. We study models with $160 < m_t < 175$ GeV, $210 < m_{\tilde{q}} < 235$ GeV, $220 < m_{\tilde{q}} < 250$ GeV, and $45 < m_{\tilde{t}} < 60$ GeV. All results are based on the analyses and models of ref. [2, 4] and are thus consistent with existing evidence for supersymmetry and with other particle physics constraints.

4 Numerical Results

In this section, we present separate results on the counting measurement of the top production cross section and kinematic measurement of the top quark mass in the supersymmetric models described in the previous section. All event simulation is performed using the Monte Carlo PYTHIA 5.7 with supersymmetric extensions [15]. The cross sections are computed at the Born level with additional QCD radiation added in the leading-log approximation. The structure functions used are CTEQ2L, and the hard-scattering scale used in the evaluation of the structure functions and the running couplings is the partonic center of mass energy (transverse mass) if the partonic final state has no (some) non-zero QCD quantum numbers. Particle energies are smeared using Gaussian resolutions based on the CDF detector, and jets are defined using the PYTHIA LUCELL subroutine. Jets are $b$–tagged with a constant efficiency when they contain a high–$p_T$ $b$–parton; the exact efficiency is stated only when a result depends upon the choice. All leptons and photons must be isolated from excess transverse energy.

To eliminate dependence on the particulars of $b$–tagging and isolation efficiencies and detector cracks, we will present some results as ratios with the SM signal expected using the same Monte Carlo routines. Where there is no SM signal expected, or just a small one, then we show an expected number of events in $100 \text{ pb}^{-1}$. First, we examine the counting measurement of the top quark production cross section. Since there are so many production processes and decay chains at work when all sparticles have weak scale masses, it is clear that a multi-channel analysis should be performed. To illustrate this point, we present a Unitarity Table (Table 1), based on a very loose set of experimental cuts, so that almost 100% of the simulated events fall into some category. On one hand, this is useful
to check that a particular model does not contradict data by predicting an anomalously high rate in some channel. On the other hand, it can point the way to unexpected features in the data, or explain why various signals are not present. This particular table is for a representative model, but displays the essential features. The columns represent various production mechanisms: (1) SM $t\bar{t}$, (2) $t\bar{t}$ with supersymmetric decays, (3) squark pair, (4) squark–gluino, (5) gluino pair, and (6) $C_i$ or $N_i$ in association with a squark or gluino. The rows represent various final states defined by the presence of charged leptons $\ell^\pm$, photons $\gamma$, and a large missing transverse energy ($E_T$) and the number of jets $n_j$ (if present, $\ell^\pm$ and $\gamma$ are explicitly noted): (a) $n_j < 3$, (b) $n_j \geq 3$, with small $E_T$, (c) $n_j \geq 3$, with large $E_T$, (d) the subset of (b) and (c) which has $n_j \geq 6$, (e) $\ell^\pm, n_j < 3$, a lepton with less than 3 jets, (f) $\ell^\pm, n_j \geq 3$ and large $E_T$, (g) $\ell^\pm, n_j \geq 3$ and small $E_T$, (h) $\ell^\pm \ell^\pm, n_j \geq 0$ with large $E_T$, (i) $\ell^\pm \gamma, n_j \geq 0$, (j) $\gamma, n_j \geq 0$, and (k) $\gamma \gamma, n_j \geq 0$. The numbers in each column represent the fraction of generated events in a particular final state. If the most important final states are accounted for, then the sum for each column should be close to unity, excluding the 6 jet final state, which is a subset of two others. Indeed, the sums vary between .98 and 1.00. This table demonstrates that we understand where the individual supersymmetric contributions go. Only after multiplying by the production cross section (and choosing more realistic cuts) for each process can we determine the observable rate. Row (c) corresponds to the standard SUSY search mode of multi–jets plus $E_T$. For the particular choices of squark and gluino masses considered here, we still elude the present experimental bound.

In the following, we present results based on more realistic cuts. There are three standard top quark search modes defined by the CDF cuts: (i) leptonic, (ii) dileptonic, and (iii) hadronic. We find substantial signals in 2 additional channels: (iv) "$W"bc$, and (v) $\gamma bc$. The channel (iv) cuts are the same as for (i), except only 2 jets are allowed. The excess number of "$W"bc$ events (where "$W"$ may have a different transverse mass since $N_1$’s carry away energy) would appear as an excess of $W$ plus 2 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–$p_T \gamma$ ($> 20$ GeV) in the central rapidity region ($|\eta^\gamma| < 1$), with 2 or more additional jets. One of the two leading jets must have a $b$-tag. As discussed earlier, channel (iv) should be limited in the Standard Model. Channel (v) events arise from the decay $N_2 \rightarrow N_1 \gamma$ in
Table 1: Unitarity Table, illustrating the fraction of events which fall into several categories for SM $t\bar{t}$ and MSSM processes.

association with top quark or top–like decays, and should have a tiny contribution from $t\bar{t}$ production alone in the Standard Model.

Table 2 summarizes the results of the counting experiments for the various models considered. The numbers have ranges, and we comment on the correlations later. In the upper portion of the table, we present fractions in each row of our Monte Carlo estimate of the process rate after cuts divided by the same estimate for SM top quark production. These numbers suggest that different values will be obtained for the top production 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 sections[14]. The row labelled $\ell^\pm, n_j < 3$ shows the predicted non–SM signal of like sign leptons; this is possible because of the Majorana nature of the gluino. We note that 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 “$W$”bc and $\gamma bj$. These numbers do not include a $b$–tagging efficiency. Also included in the $\gamma bj$ sample is the expected number of events from $C_i(\rightarrow b\ell)N_2(\rightarrow N_1\gamma)$ 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
Table 2: 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.

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, \( m_{\tilde{t}_1} = 165 \) GeV, \( m_{\tilde{q}} = 220 \) GeV, \( m_{\tilde{g}} = 210 \) GeV, \( m_{\chi_1^0} = 38 \) GeV, and \( m_{\tilde{t}_1} = 45 \) 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, \( m_{\chi_1^0} = 38 \) GeV, and \( m_{\tilde{t}_1} = 50 \) GeV, the numbers are 5.7, 5.3, and 6.3 pb.

Some of the larger apparent rate for top quark production for SUSY processes comes from the increased cross section for smaller \( m_t \). We use the resummed prediction, which is similar to the NLO number. The production of squarks and gluinos, on the other hand, are calculated only at LO, and could receive a substantial NLO correction. Based on Ref. [16], we estimate that our squark and gluino production cross sections (which are evaluated using the transverse mass as the factorization scale) could be increased (but not decreased) by as much as 40%. We have not included this \( K \)-factor in our study. 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 2. It is remarkable how naturally the apparent cross section values span the experimentally allowed values.
Figure 1: The distribution of $\gamma bj$ events expected in 100 pb$^{-1}$. There are contributions from the $C_iN_2$, $t\bar{t}$, and $\tilde{q}, \tilde{g}$ production processes.

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 $\gamma b E_T + \text{jets}$ in Fig. 1, resulting from models with $m_t=160$ GeV. They are of particular interest because there is no parton-level SM source of such events, and our MSSM scenario predicts a significant number. There are three sources: $q\bar{q} \rightarrow C_i(\to b\tilde{t}^*)N_2(\to \gamma N_1), q\bar{q}(gg) \rightarrow t(\to bW(\to jj))\bar{t}(\to \tilde{t}^*N_2(\to \gamma N_1))$, with $\tilde{t} \to cN_1$, and cascade decays from $q\bar{q}$, $q\bar{g}$, $g\bar{g}$, $gN_i$, $gC_i$, $\tilde{q}N_i$, $\tilde{q}C_i$, populating different regions of the plot. The $C_iN_2$ and $t\bar{t}$ signals depend mostly on the supersymmetric interpretation of the CDF event and the postulate of a light stop squark to explain $R_b$; their signal may be present regardless of the other squark and gluino masses. 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.

In addition to the top quark measurements based on counting events, there are kinematic measurements, such as the reconstructed top mass, the $t\bar{t}$ invariant mass, the transverse momentum of the pair, etc. The explicit reconstruction is a difficult task. Not all of the
Reconstructed Mass of $t\bar{t}$ (GeV) 

Events in $110 \text{ pb}^{-1}/(25 \text{ GeV})$

$W^+ \geq 3$ jets data

$\varepsilon_{\text{tag}} = 0.35$

SM, $m_t = 170$ GeV

MSSM, $m_t = 160$ GeV

Figure 2: The invariant mass distribution of the $t\bar{t}$ pair for SM and MSSM top quark production compared with the CDF data.
apparent top quark signal in our models comes from real top quarks, but a substantial fraction does. Rather than attempt an explicit reconstruction for such detector dependent quantities, we have tried to determine where we should expect agreement with and deviation from the SM distributions. We identify the partonic top and anti–top quarks in our generated events and use these to calculate the invariant mass and transverse momentum of the $t\bar{t}$ pair. In the process, we ignore those events which have only one or no real top quarks, but scale those events with two top quarks to the full rate including the discarded events. The invariant mass distribution from SM top quark production alone with $m_t=170$ GeV, for our MSSM with $m_t=160$ GeV, and with the CDF data is displayed in Fig. 2. The CDF data is from [17]. While we have only performed a crude simulation, we believe this figure demonstrates that our MSSM is consistent with the data. This consistency is understandable. Since top quarks are coming from gluino decay 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 transverse momentum of the $t\bar{t}$ pair is displayed in Fig. 3 for the same conditions as for Fig. 2. Here, we have not smeared the distributions, but we observe that the MSSM distribution is broader than that expected in the SM. This too is expected; the two–body decay of the gluinos tends to randomize the top quark direction, removing the approximate balance in $p_T$ expected from SM $t\bar{t}$ production. The expected SM $t\bar{t}$ distribution displayed in Ref. [17] is 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 $W(\rightarrow \ell\nu)+$jets mode. The lepton and the $E_T$ 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 $E_T$ from cascade decays down to $N_1$. The expected distributions for the transverse mass and the CDF data are shown in Fig. 4. The naive expectation that the MSSM distribution must be distinguishably different is not fulfilled. The CDF data is from [18].

Since many of the top events have 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. For example, we have noticed that the invariant mass distribution of the leptons in dilepton events is softer than for SM top events. This indicates that the mass kinematically
Figure 3: The transverse momentum distribution of the $t\bar{t}$ pair for the SM and MSSM compared to the data. The generated distributions have not been smeared.

Figure 4: The transverse mass of the lepton and $E_T$ for the SM and MSSM compared to the data.
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.

5 Conclusions

We have argued that existing data is consistent with the possibility that hundreds of squarks and gluinos have been produced at FNAL. Squarks decay mainly into gluinos, charginos, and neutralinos, gluinos into top quarks and stop squarks, and $\text{BR}(t \rightarrow \tilde{t}N_i)$ 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, and of course for the existence of supersymmetry in nature.

Acknowledgments

The authors thank E.L. Berger, H. Frisch, E. Kovacs, T. LeCompte, L. Nodulman, M. Strovink, S. Ambrosanio, G.D. Kribs and S.P. Martin for useful discussions.
References

[1] S. Park, “Search for New Phenomena in CDF”, 10th Topical Workshop on Proton-Antiproton Collider Physics, edited by Rajendran Raja and John Yoh, AIP Press, 1996.

[2] S. Ambrosanio, G.L. Kane, G.D. Kribs, S.P. Martin, S. Mrenna, Phys. Rev. Lett. 76 (1996) 3498.

[3] S. Dimopolous, M. Dine, S. Raby, S. Thomas, Phys. Rev. Lett. 76 (1996) 3502.

[4] J.D. Wells, G.L. Kane, Phys. Rev. Lett. 76 (1996) 869; See also Ref. [5] for other \( R_b \) analyses.

[5] A. Djoudi et al., Nucl. Phys. B349 (1991) 48; M. Boulware and D. Finnell, Phys. Rev. D44 (1991) 2054; J.D. Wells, C. Kolda, and G.L. Kane, Phys. Lett. B338 (1994) 219; D. Garcia and J. Sola, Phys. Lett. B354 (1995) 335; G.L. Kane, R.G. Stuart, and J.D. Wells, Phys. Lett. B354 (1995) 350; A. Dabelstein, W. Hollik, and W. Mösle, [hep-ph/9506251]; P. Chankowski and S. Pokorski, Phys. Lett. B366 (1996) 188; J. Ellis, J. Lopez and D. Nanopoulos, [hep-ph/9512288]; E. Simmons and Y. Su, [hep-ph/9602267]; P. Chankowski and S. Pokorski, [hep-ph/9603310].

[6] G.L. Kane and J.D. Wells, [hep-ph/9603336], to appear in Phys. Rev. Lett.

[7] E.L. Berger and H. Contopanagos, Phys. Lett. B361 (1995) 115; S. Catani, M.L. Mangano, P. Nason, and L. Trentadue, [hep-ph/9602208], CERN-TH–96–86.

[8] R.M. Barnett, J.F. Gunion and H.E. Haber, Phys. Lett. B315 (1993) 349.

[9] J. Ellis and S. Rudaz, Phys. Lett. B128 (1983) 248; I.I. Bigi and S. Rudaz, Phys. Lett. B153 (1985) 335; K. Hikasa and M. Kobayashi, Phys. Rev. D36 (1987) 724; H. Baer et al., Phys. Rev. D44 (1991) 725.

[10] S. Mrenna and C.-P. Yuan, Phys. Lett. B367 (1996) 188.

[11] J. Incandela, FERMILAB–CONF–95/237–E.
[12] J. Sender, hep-ph/9602354, UH–511–843–96.

[13] D.R. Claes, FERMILAB–CONF–95/186–E.

[14] F. Abe et al., Phys. Rev. Lett. 73, 225 (1994);
    S. Abachi et al., Phys. Rev. Lett. 72, 2138 (1994).

[15] H.U. Bengtsson and T. Sjöstrand, Comp. Phys. Comm. 46 (1987) 43; S. Mrenna,
    “Simulating Supersymmetry With PYTHIA 5.7 and JETSET 7.4,” CITHE–68–1987,
    July 1995.

[16] W. Beenakker, R. Höpker, M. Spira, and P.M. Zerwas, Z. Phys. C69 (1995) 163.

[17] G.F. Tartarelli, CDF/PUB/TOP/PUBLIC/3664.

[18] J. Incandela, FERMILAB–CONF–95/152–E, CDF/PUB/TOP/3209.