SEARCHES FOR NEW PHENOMENA AT THE TEVATRON

Marc Paterno
Department of Physics and Astronomy
University of Rochester, Rochester, NY 14627-0171

Representing the CDF and DØ Collaborations

ABSTRACT

We present an update on the current status of some new particle searches at the Tevatron. We report on searches for first generation scalar leptoquarks in the $eejj$ and $e\nu jj$ channels, searches for the particles of supergravity in the multijet + missing transverse energy and dielectron channels, searches for charginos and neutralinos in the single photon and diphoton channels, and a search for a light c squark in an R-parity violating supersymmetry model.

1 The Tevatron and Its Detectors

The Tevatron at the Fermi National Accelerator Laboratory is the highest energy collider in the world. It collides counter-rotating beams of protons and antiprotons at a center-of-momentum energy $\sqrt{s}$ of 1.8 TeV. An excellent introduction to the Tevatron accelerator complex is found in Ref. 1. The 1992–1996 run of the Tevatron concluded with delivery of an integrated luminosity in excess of 100 pb^{-1} to each of the two general-purpose collider detectors, CDF and DØ.

Detailed descriptions of each detector can be found in Refs. 2–4. CDF (Collider Detector at Fermilab) is a general-purpose detector, located at the B0 high-luminosity interaction region of the Tevatron. Closest to the interaction region is a silicon vertex detector, surrounded by a large wire chamber, both of which are located inside a 1.4 Tesla superconducting solenoid magnet. Surrounding the tracking system is a lead-scintillator calorimeter and a muon spectrometer. DØ is a general-purpose detector, located at the DØ high-luminosity interaction region of the Tevatron. It consists of a nonmagnetic central tracking system, surrounded by a hermetic uranium–liquid argon sampling calorimeter, and a toroidal muon spectrometer.

2 Why Search?

Searches for new physics at the high-energy frontier test the Standard Model (SM) by seeking phenomena beyond it—we are less likely to discover new physics if we study only standard processes.

The searches we perform may be grouped into two broad categories: some are driven primarily by *theory*, and some by *data*. For example, *supersymmetry* is a feature often incorporated in extensions to the SM. Although there has been little experimental evidence of supersymmetry, the theory is of sufficient interest that we consider searching for its existence. Two examples of data-motivated searches are the current upsurge of interest in leptoquarks and in gauge-mediated supersymmetry models; the observation of an excess of high-momentum transfer events at HERA spurred interest in leptoquarks, while the observation of a possible $ee\gamma\gamma$ event with large transverse momentum imbalance (often called missing transverse energy, or $\not\!\!E_T$) caused an increased interest in gauge-mediated supersymmetry.

Searches deal with some of the most important theoretical issues in HEP. Some of the questions addressed by the searches discussed in this paper are "Why is the number of quark generations equal to the number of lepton generations?" and "Why is the expected mass of the Higgs so much less than the Planck mass?" It is through searches for physics beyond the predictions of the Standard Model that we may find the information that allows us to answer these questions. In this paper, we present the status of these searches as of the time of the conference. The reader should note that many of these analyses have been updated since that time.

3 Standard Model: Generations

The Standard Model has three generations of leptons and an equal number of generations of quarks. To date, all searches for additional leptons and quarks have given null results. Measurements of the width of the Z boson preclude the existence of another light neutrino species.[5] Furthermore, to prevent anomalies, the Standard Model requires that there be an equal number of generations of leptons and quarks. However, the SM contains no explanation of why the number of quark and lepton generations should be equal.

One possible explanation for this equality could be the existence of a symmetry that relates quarks and leptons. Such a symmetry could imply the existence of a particle that has the properties of both leptons and quarks: these hypothetical particles are called leptoquarks.[6–8]

4 Leptoquarks

4.1 A Bit of Theory

Leptoquarks (LQ) are hypothetical particles combining properties of leptons and quarks. They are color triplet bosons (either scalars or vectors), carrying fractional electric charge, nonzero baryon number B, and lepton number L. Most models containing leptoquarks contain three generations, corresponding to the three generations of leptons and quarks. Mixing between generations would give rise to flavor-changing neutral currents, which are strongly constrained by experimental data[9–11]; therefore the leptoquarks of a given generation would decay into

one lepton and one quark of the corresponding generation; *e.g.* $LQ_1 \to \bar{e}\bar{u}$. Here we have used the common convention for leptoquarks LQ and antileptoquarks $\overline{LQ}$.

There can be several different types of leptoquarks in a single generation, each of which has different quantum numbers, corresponding to any of the four possible combinations of the charged or neutral lepton, and the u- or d-type quark of that generation. Each different type of leptoquark then has well-specified decay modes and branching fractions. Partly for historical reasons, and partly for additional generality, in experimental searches we typically introduce a parameter β, which is the branching fraction for the leptoquark decay to the charged lepton (and a quark) of the corresponding generation. Since we do not generally identify the type of quark in our detectors, we make no such distinction between u- and d-type quarks in the decay products.

Leptoquarks, if they exist and have sufficiently small mass, should be pair-produced at the Tevatron through the strong interaction. Searches for leptoquarks at the Tevatron are thus not sensitive to the strength of the LQ-ℓ-q coupling, except that it not be so small that the LQ escapes the detector before decaying.

The interest in leptoquarks was increased by the observation of an excess of high-momentum transfer (high Q^2) events in e^+p collisions at HERA.[12,13] If it is not due to a statistical fluctuation, this excess could most easily be explained as the result of the production and decay of first-generation leptoquarks with a mass of approximately 200 GeV/c^2. Accordingly, most attention has been paid to searches for first-generation leptoquarks, LQ_1.

4.2 First-Generation Leptoquark Searches at the Tevatron

The signature for the production and decay of leptoquark pairs depends on the branching fraction to charged leptons, β. For $\beta = 1$, the signature is two isolated leptons plus two jets; for $\beta = 0$ the signature is two jets plus large missing transverse energy. For intermediate values of β, three final states are possible: $\ell\ell jj$, $\nu\nu jj$, and $\ell\nu jj$. To obtain the best possible limits, one must combine the results for searches in all channels.

Both CDF and DØ have preliminary results from searches for first-generation leptoquarks, in the $eejj$ and $e\nu jj$ channels. We present these results in the following sections.

4.2.1 CDF

CDF has searched for first-generation leptoquarks in the $eejj$ channel in a data sample corresponding to an integrated luminosity of 110 pb^{-1}. The major backgrounds to this channel were the pair production of t quarks in the dielectron channel ($t\bar{t} \to (b\bar{e}\nu_e)(\bar{b}e\bar{\nu}_e)$) and electroweak production of dielectron pairs (Drell-Yan and Z boson $\to ee$) in association with jets.

Initial selection consisted of the requirement of two electrons with $E_T >$ 25 GeV, and two jets, with $E_{T1} >$ 30 GeV and $E_{T2} >$ 15 GeV; the invariant mass m_{ee} of the dielectron pair was required to be away from the Z mass ($m_{ee} <$ 76 GeV/c^2 or $m_{ee} >$ 106 GeV/c^2); and the separate sums of electron and jet transverse energies were each required to be greater than 70 GeV ($E_T^{e_1} + E_T^{e_2} >$ 70 GeV and $E_T^{j_1} + E_T^{j_2} >$ 70 GeV). In the data, 12 events were observed to satisfy these requirements. Final event selection was based on requiring events to have electron-jet invariant masses consistent with the decay of a pair of objects with the same mass. The two possible pairs of electron-jet invariant masses were calculated, and the pairs with the smallest difference in mass were designated as M_{ej_1} and M_{ej_2}. Events were then required to satisfy $\delta M < 0.2 M_{LQ}$, where $\delta M = |M_{ej_1} - M_{ej_2}|$, and M_{LQ} is the mass of the hypothetical leptoquark; discrete values of M_{LQ} ranging from 140 GeV/c^2 to 240 GeV/c^2 were used in this calculation. This selection requirement is illustrated in Fig. 1, which also shows the 12 events passing the penultimate selection requirement, as well as the distribution for a sample of simulated leptoquark events, with $M_{LQ} =$ 200 GeV/c^2. The final efficiency forleptoquarks of this mass was 25%.

In the final sample, no event has an invariant mass greater than 140 GeV/c^2. Three events pass all selection criteria, compared with an expected 5.8 $\pm$ 2.2 events from SM sources. In the absence of evidence of a signal, this result was used to set an upper limit (at the 95% confidence level) on the cross section for first-generation leptoquark production, shown in Fig. 2. Interpreted as a lower limit on the mass of the first-generation leptoquark, this result excludes first-generation leptoquarks with $\beta = 1$, and mass less than 213 GeV/c^2 at the 95% confidence level.

The CDF Collaboration also has preliminary results from a search for leptoquarks in the $e\nu jj$ channel, using a data sample with an integrated luminosity of 110 pb^{-1}. This search required one electron with $E_T >$ 20 GeV; $\not{E}_T >$ 35 GeV;

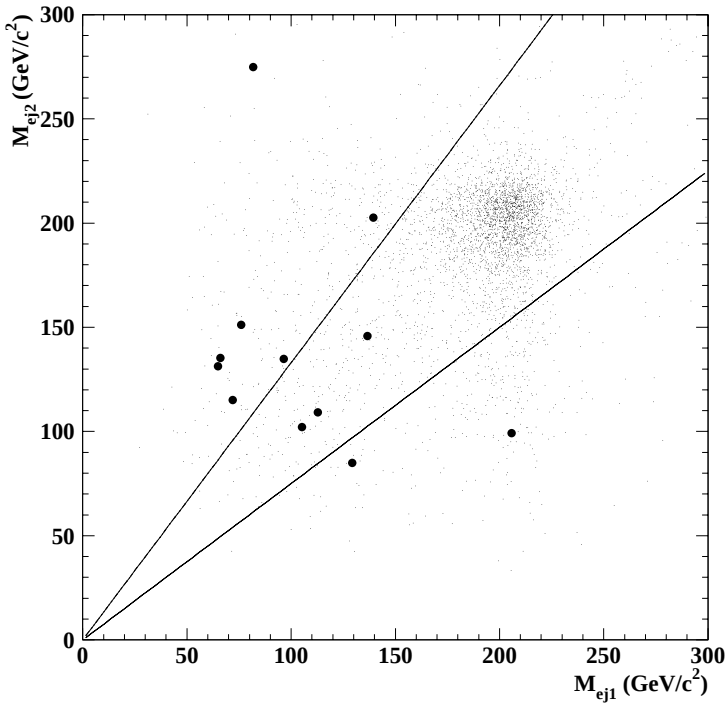

Fig. 1. The distribution of m_{ej_1} and m_{ej_2} for the data (dark dots), and for a simulated sample of leptoquark events ($m_{LQ} = 200$ GeV/c^2), from the CDF $eejj$ analysis. The region between the solid lines is the signal region.

no second lepton; at least two jets, one with $E_T > 30$ GeV and a second with $E_T > 15$ GeV, and with the sum of all jets' transverse energies greater than 80 GeV; no b-tag for any jet; and transverse mass $M_T(e\nu) > 120$ GeV. After these requirements, two events were observed in the data, with a total background prediction of 3.2 ± 0.8 events (2.4 ± 0.7 events from $t\bar{t}$ production, and 0.8 ± 0.4 events from W+2 jet production). The final selection was based on reconstructing the invariant masses of the two lepton-jet systems. Both combinations of ν-jet transverse mass and e-jet invariant mass were calculated, and the pairing that gave the smallest difference was selected. To select signal events, a signal region in the $M_T(\nu j)$ versus M_{ej} plane was defined; the optimal region varied for different hypothetical leptoquark masses. For $M_{LQ} = 180$ GeV/c^2, the signal region was defined as $90 < M_T(\nu j) < 290$ GeV/c^2, and $130 < M_{ej} < 230$ GeV/c^2. One event remained in this signal region. The final efficiency for leptoquarks with a mass of 180 GeV/c^2 was 16%. In the absence of a significant signal, this result

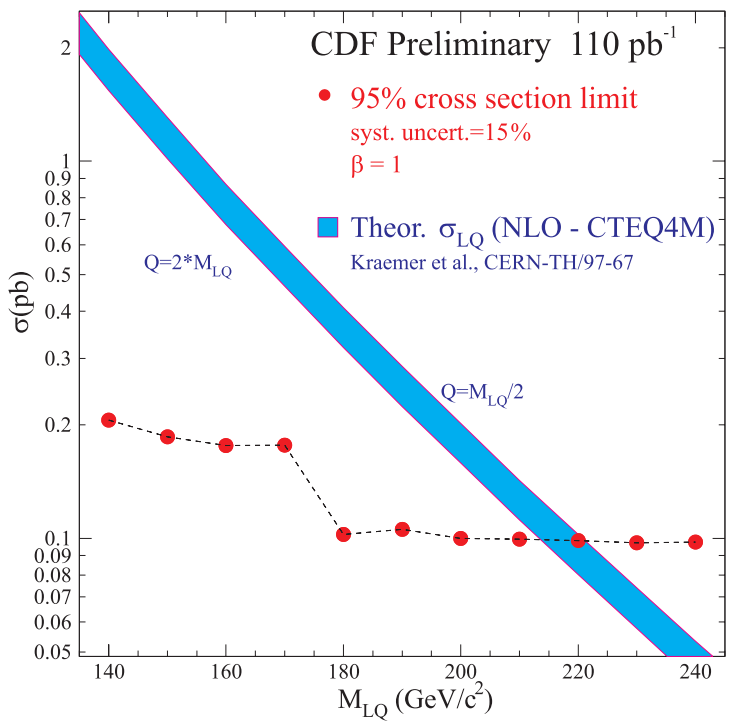

Fig. 2. The cross section limit for the production of first-generation leptoquarks from the CDF experiment search in the $eejj$ channel. For a branching fraction to charged leptons $\beta = 1$, the resulting lower limit on the leptoquark mass is 213 GeV/c^2, at the 95% confidence level.

was used (with no background subtraction) to exclude leptoquarks with $\beta = 0.5$ and mass less than 180 GeV/c^2 at the 95% confidence level.

4.2.2 DØ

The DØ experiment has also performed searches for first-generation leptoquarks, in both the $eejj$ and $e\nu jj$ channels.

The $eejj$ channel search was conducted using a data sample corresponding to an integrated luminosity of 123 pb^{-1}. In this search, initial data selection required two electron candidates (electromagnetic calorimeter clusters) with $E_T > 20$ GeV, and two jets with $E_T > 15$ GeV. The distance $\mathcal{R} = \sqrt{\delta\phi^2 + \delta\eta^2}$ between each electron and jet was required to satisfy $R > 0.7$, and the invariant mass m_{ee} of the dielectron system was required to be away from the Z mass peak: $m_{ee} <$ 82 GeV/c^2 or $m_{ee} >$ 100 GeV/c^2. Finally, at least one electron candidate was required to have a matching track in the central tracking volume. A total of

101 events passed these initial requirements, with a background expectation of 93 $\pm$ 14 events from all SM sources (67 $\pm$ 13 events from Drell-Yan ee + 2 jet production, 24 $\pm$ 4 events from four-jet production and double mistaken electron identification, and 1.8 $\pm$ 0.7 events from $t\bar{t}$ production).

Final event selection was based on a transverse energy variable S_T, defined as the sum of the transverse energies of both electrons, and all jets with $E_T > 15$ GeV. The selection threshold for this variable was set to give an expected background near 0.4 events; the final threshold was $S_T > 350$ GeV. The distribution of S_T for the 101 event initial selection compared very well with the expectations from SM sources, as shown in Fig. 3. No event had $S_T > 320$ GeV. The final signal efficiency varied from 16% for leptoquarks with a mass of 160 GeV/c^2, increasing to 36% for leptoquarks with a mass of 250 GeV/c^2.

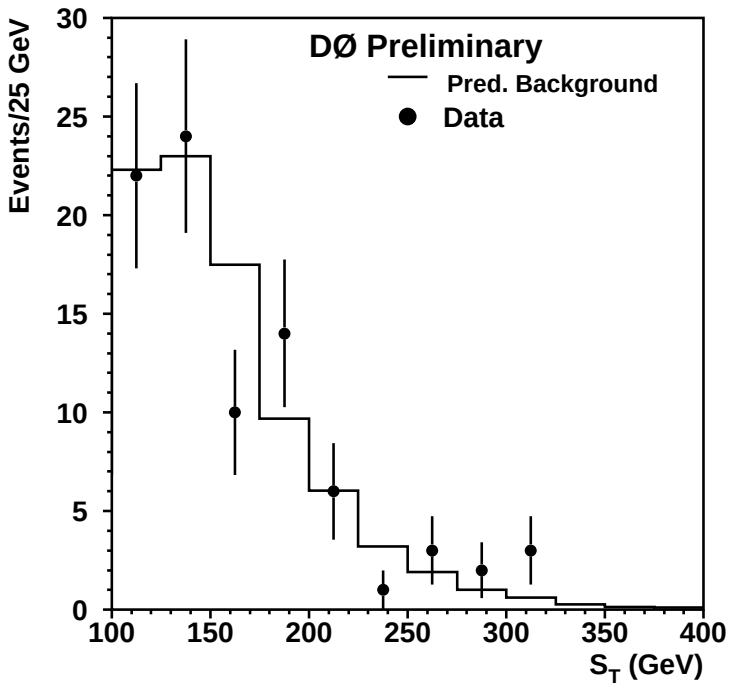

Fig. 3. The distribution of the transverse energy variable S_T (defined in the text) for the DØ first-generation leptoquark search in the $eejj$ channel. The solid line shows the prediction from Standard Model sources, and the dots show the data.

Since no signal for leptoquark pair production was observed, this result was used to determine an upper limit (at the 95% confidence level) on the cross section for leptoquark production of 0.09 pb for leptoquark masses of 180 GeV/c^2, improving slightly with increasing mass to 0.07 pb at a leptoquark mass of 250 GeV/c^2,

as shown in Fig. 4. When compared with the predicted leptoquark production cross section, this led to the exclusion (at the 95% confidence level) of leptoquarks with $\beta = 1$ and mass less than 225 GeV/c^2.

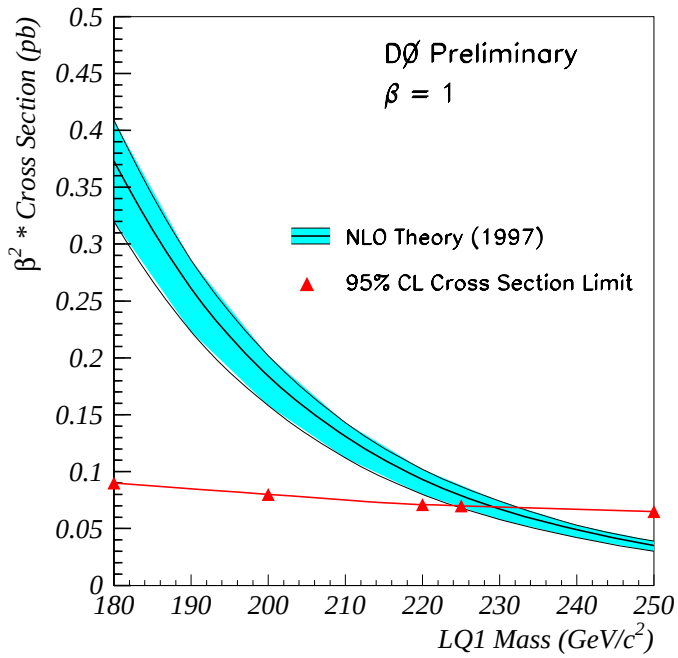

Fig. 4. The upper limit (at the 95% confidence level) on the cross section for the production of first-generation leptoquarks, from the DØ experiment search in the $eejj$ channel. For a branching fraction to charged leptons $\beta = 1$, the resulting lower limit on the leptoquark mass is 225 GeV/c^2, at the 95% confidence level.

In the $e\nu jj$ channel, DØ also has preliminary results, based on a data sample with an integrated luminosity of 103 pb^{-1}. The basic event selection required one electron with $E_T > 25$ GeV, two jets with $E_T > 25$ GeV, $\not{E}_T > 40$ GeV and with $\delta\phi$ between the $\not{E}_T$ and each jet satisfying $\delta\phi > 0.25$ and $|\pi - \delta\phi| > 0.25$. An additional requirement was $S_T > 170$ GeV, where S_T was defined as the sum of the transverse of the electron plus the transverse energies of those jets with $E_T > 15$ GeV. Finally, events with isolated muons were excluded, since muons are not part of the first-generation leptoquark signature. This preliminary selection yielded 32 events, with an expected total of 30 $\pm$ 5 events from all SM sources (20 $\pm$ 4 events from $W + 2$ jet production, 9.0 $\pm$ 2.7 events from $t\bar{t}$ production, and 1.1 $\pm$ 0.4 events from three-jet production with misidentification of one jet

as an electron). Events were required to have an electron-$\not{E}_T$ transverse mass greater than 100 GeV/c^2. One event in the data passes this requirement; this event is also a t-quark candidate. Standard Model background predictions were 0.5 ± 0.3 events from $W + 2$ jet production, $0.4 \pm 0.4 \pm 0.2$ events from three-jet production and electron misidentification, and 1.5 ± 0.5 events from $t\bar{t}$ production, for a total background expectation of 2.5 ± 0.6 events.

The final selection requirement is based on a variable $\delta M = |M_{ej} - M_{LQ}|/M_{LQ}$, where M_{LQ} is the hypothesized leptoquark mass, and M_{ej} is the electron-jet invariant mass; for each M_{LQ}, the jet which gave the smallest δM was chosen. Based on Monte Carlo studies of signal efficiency and background expectations, a requirement of $\delta M < 0.2$ was applied to the data; no events passed. The expected background from all SM sources was less than 0.4 events.

Having observed no signal for leptoquark production, this result was used to exclude (at the 95% confidence level) leptoquarks with $\beta = 0.5$ and with mass below 158 GeV/c^2. In combination with the $eejj$ channel search, leptoquarks with mass below 195 GeV/c^2 are excluded, for $\beta = 0.5$.

4.3 Leptoquark Summary

Together, these analyses exclude the leptoquark interpretation of the excess of high Q^2 events observed by the H1 and ZEUS Collaborations. A final resolution to the cause of this excess—new physics of another variety or statistical fluctuation—will have to wait for the additional data now being collected by the HERA experiments.

5 Supersymmetry

Supersymmetry (SUSY)[15] is a symmetry that relates bosons and fermions. In a SUSY model, each particle has a partner with the same quantum numbers, but with a spin that differs by one half. Supersymmetry is interesting for many reasons: it can help solve the quadratic divergence in the Higgs sector of the SM; it can help resolve the hierarchy problem in grand unified (GUT) models; it raises the value of the scale for grand unification to a level at which predicted proton decay rates are consistent with experimental bounds.[16–21]

Because no known particle has the appropriate qualities to be the super partner of another, the minimal SUSY extension of the SM doubles the particle spectrum.

In addition, SUSY models require two Higgs doublets, resulting in a total of four Higgs bosons, three neutral and one charged.

The particle spectrum of the minimal supersymmetry extension of the Standard Model (MSSM) thus includes

- quarks q (spin $\frac{1}{2}$) and their partners, squarks $\tilde{q}$ (spin 0);
- leptons ℓ (spin $\frac{1}{2}$) and their partners, sleptons $\tilde{\ell}$ (spin 0);
- gluons g (spin 1) and their partners, gluinos $\tilde{g}$ (spin $\frac{1}{2}$);
- charged Higgs $H^{\pm}$ (spin 0) and charged weak vector boson $W^{\pm}$ (spin 1) and their partners, the mixed chargino states $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^{\pm}$ (spin $\frac{1}{2}$);
- the neutral Higgs particles h^0, A^0, and H^0 (spin 0), the photon and the Z boson (spin 1), and their partners, the mixed neutralino states $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$, and $\tilde{\chi}_4^0$ (spin $\frac{1}{2}$).

By convention, the chargino and neutralino mass eigenstates are numbered in order of increasing mass.

Since no known particle has the correct mass and quantum numbers to be the super partner of any other known particle, SUSY (if it exists at all in nature) must be a broken symmetry. In most models, supersymmetry breaking is put explicitly into a "hidden sector" of very massive particles, and interactions between these particles and the particles of the low-energy spectrum communicate the supersymmetry breaking to the low-energy spectrum. The popular choices for the messenger interaction are gravity, in supergravity (SUGRA) models, or gauge interactions, in gauge-mediated supersymmetry breaking (GMSB) models. SUGRA and GMSB models each lead to distinctive and different predictions.

The introduction of SUSY into the SM Lagrangian suggests the identification of a new multiplicative quantum number, called R-parity (R_P). For the particles of the SM, including the Higgs bosons, $R_P = +1$; for their partners, $R_P = -1$. If R_P is conserved, then $R_P = -1$ particles (sparticles) must be produced in pairs, and the decay of each sparticle must include one sparticle; the result is that the lightest sparticle (the LSP) must be stable. In order to avoid cosmological constraints, in R_P-conserving models the LSP must carry neither electric charge nor color.[22]

In SUGRA models, the natural choice is the lightest neutralino, $\tilde{\chi}_1^0$; in GMSB models, the natural choice is the gravitino, $\tilde{G}$, which is the partner to the graviton.

Models in which R_P is not conserved must be constructed to guarantee stability against proton decay; this is generally done by including R_P-violating terms which produce either lepton number violation or baryon number violation, but not both. Such models predict a phenomenology significantly different from R_P-conserving models.

One can see that a wide variety of models involving supersymmetry can be defined. The two Tevatron collaborations have conducted searches for evidence of each of the types of models listed above; in the following sections, we present some of these searches.

5.1 Supergravity Searches

The choice of gravity as the mediator of supersymmetry breaking leads to the identification of the lightest neutralino ($\tilde{\chi}_1^0$) as the LSP. Since the $\tilde{\chi}_1^0$ interacts with normal matter only through the exchange or production of (presumably heavy) sparticles, the cross section for interaction in a collider detector is very small. The characteristic signature of supergravity (SUGRA) models is therefore $\not{E}_T$ resulting from the escape of the pair of $\tilde{\chi}_1^0$s.

The most interesting SUGRA models are those which are also grand unified (GUT) models. In such models, all the gauge interactions are unified at some mass scale M_G. At this scale, all the gauginos (gluinos, charginos, and neutralinos) share a common mass, denoted by $m_{1/2}$. It is customary to make an additional assumption of scalar unification: At the scale M_G, all the scalar partners of the quarks and leptons share a common mass denoted by m_0. Furthermore, the trilinear couplings between Higgs fields, leptons, and quarks are assumed to be specified by a common coupling constant, A_0. Finally, to completely specify a model, two additional parameters must be set. One must assign a value to $\tan(\beta)$, the ratio of the vacuum expectation values of the two Higgs doublets, and also specify the sign of μ, a parameter in the Higgsino mixing matrix, for which the magnitude is set by requiring the correct mass of the Z boson. We shall refer to the SUGRA-GUT model defined by these parameters as *minimal low-energy supergravity*, or MLES.

After the specification of these five parameters, the masses and mixings of all particles are calculable, as are decay branching fractions and production cross sections.

5.1.1 SUGRA Searches at DØ

For much of MLES parameter space accessible at the energy of the Tevatron, the dominant sparticle production mechanism would be pair production of the strongly interacting sparticles: $p\bar{p} \to \tilde{g}\tilde{g}$, $\tilde{q}\bar{\tilde{q}}$, $\tilde{g}\tilde{q}$, and $\tilde{q}\tilde{q}'$.

There are many decay modes available for both squarks and gluinos, the details of which depend upon the details of the particle mass spectrum. This leads to a rich phenomenology, of which we are just beginning to take advantage. For a wide range of parameter values, the most common decay modes of squarks and gluinos lead to final states consisting only of quarks and the LSP. For much of MLES parameter space, the "direct decays" $\tilde{q} \to q\tilde{\chi}_1^0$ or $\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$ are not common, and instead decays often proceed through a cascade of sparticles, including charginos and neutralinos. For example, one common squark decay could be $\tilde{q} \to q\tilde{g}$ followed by $\tilde{g} \to \bar{q}'q'\tilde{\chi}_2^0$ followed by $\tilde{\chi}_2^0 \to q''\bar{q}''\tilde{\chi}_1^0$; the final result in this case would be $\tilde{q} \to q\bar{q}'q'q''\bar{q}''\tilde{\chi}_1^0$. The signature for such production and decay is the observation of multiple jets and $\not{E}_T$. Although the number of quarks appearing in the decay may be large, most often they are not all individually distinguishable as jets. To keep reasonable efficiency for the detection of such events, typically one requires a more modest number of jets.

The DØ Collaboration has performed a search for squarks and gluinos, based on an integrated luminosity of 79 pb^{-1}, using the signature of three jets and large $\not{E}_T$. This approach differs from earlier analyses[23,24] in that this search uses the constraints of MLES to determine the particle spectrum, rather than more *ad hoc* assumptions. The major backgrounds included the SM sources of high momentum neutrino production, in association with jets: $t\bar{t}$ pair production, W and Z boson production in association with jets, and WW and WZ associated production. Also significant was the instrumental background of SM multijet production, with $\not{E}_T$ as a result of mismeasurement, either of one or more jet energies or of the vertex location.

Initial event selection required $\not{E}_T > 75$ GeV; at least three jets with $E_T > 25$ GeV, one of which was required to have $E_T > 115$ GeV, and all of which were required to be isolated in azimuth from the direction of the $\not{E}_T$; no isolated electrons or muons with $E_T > 15$ GeV; and to have $H_{T2} = \sum E_T^{\text{jets}} > 100$ GeV, where the sum is taken over all jets with $E_T > 25$ GeV, but does not include the leading E_T jet. To reduce the background from multiple interactions, the

central jet with greatest E_T was required to be consistent with emanation from the primary interaction vertex. A total of 9.3 $\pm$ 3.5 events was expected from all SM sources (3.1 $\pm$ 1.1 from $t\bar{t}$ production, 2.7 $\pm$ 1.0 from W and Z production, and 3.5 $\pm$ 2.6 from SM multijet production); 15 events were observed in the data.

When one considers different regions in the $(m_0, m_{1/2})$ parameter plane, one finds that for low m_0 and large $m_{1/2}$, the squark pair production dominates, and for large m_0 and small $m_{1/2}$, gluino pair production dominates. Squark production tends to produce fewer jets, each with larger E_T, while gluino production tends to produce more jets, with somewhat lesser E_T. The amount of $\not\!\!E_T$ produced also varies, because of the changing mass of the $\tilde{\chi}_1^0$, and because of the changes in the cascade decays. For these reasons, final selection criteria for this analysis were determined by varying the $\not\!\!E_T$ and H_{T2} thresholds applied to different regions in the $(m_0, m_{1/2})$ parameter space. Thresholds were chosen to maximize the figure of merit $S/\delta B$, where S is the expected number of events from the signal processes, and δB is the total uncertainty in the background prediction, including both statistical and systematic uncertainty. The final $\not\!\!E_T$ thresholds ranged from 75 to 100 GeV, and the H_{T2} thresholds from 100 to 160 GeV. For none of the final selection criteria was there an observation of a significant excess of events beyond SM predictions. Therefore, this result was used to determine a 95% C.L. exclusion contour in the $(m_0, m_{1/2})$ plane; the exclusion contour is shown in Fig. 5.

In addition to the multijet + $\not\!\!E_T$ search, DØ has also performed a search for supersymmetry in the dielectron + jets + $\not\!\!E_T$ channel. This search takes advantage of the smaller SM backgrounds for dielectron production. In a data sample corresponding to an integrated luminosity of 90 pb^{-1}, this search looked for events with exactly two electrons with $E_T > 15$ and $|\eta| < 1.2$ or $1.4 < |\eta| < 2.5$, two or more jets with $E_T > 20$ GeV and $|\eta| < 2.5$, and $\not\!\!E_T > 25$ GeV. Events with $79 < m_{ee} < 103$ GeV/c^2 were removed as possible $Z \to ee$ events, unless the event also had $\not\!\!E_T > 40$ GeV. The calculated background expectation from SM sources was 2.9 $\pm$ 1.3 events; the major contributions were from $t\bar{t}$ production (1.1 events), $Z \to ee$ (1.0 events) and multijet events in which two jets were misidentified as electrons (0.4 events). A total of two events was observed in the data, consistent with SM expectations. In the absence of a signal, this result was used to determine an exclusion contour in the $(m_0, m_{1/2})$ plane; the contour is shown (along with that of the DØ multijet + $\not\!\!E_T$ search) in Fig. 5.

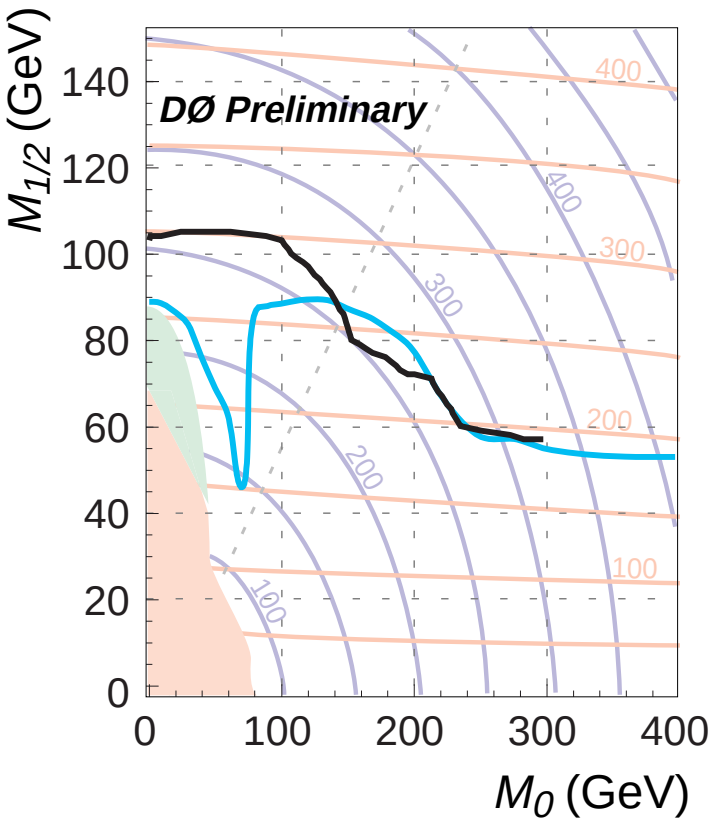

Fig. 5. The exclusion contour for the DØ supergravity searches. The region below the dark line is excluded at the 95% C.L. by the multijet + $\not\!\!E_T$ analysis, and the region below the light line is excluded at the 95% C.L. by the dielectron + jets + $\not\!\!E_T$ analysis. The nearly horizontal lines are contours of constant gluino mass, and the elliptical lines are contours of constant squark mass; the labels show the relevant particle's mass in GeV/c^2.

The most striking feature of the exclusion contour from the dielectron channel analysis is the dip in the region near $m_0 = 90$ GeV/c^2. This dip occurs because of the complicated relationships between the sparticle masses in MLES. For most of the $(m_0, m_{1/2})$ parameter space, the major source of dielectron events is the decay $\tilde{\chi}_2^0 \to ee\tilde{\chi}_1^0$, where the $\tilde{\chi}_2^0$ is either produced in the decay of a squark or gluino, or is produced directly, in association with a chargino or other neutralino. In the region of the dip, however, the mass of the $\tilde{\nu}$ is less than that of the $\tilde{\chi}_2^0$, which opens the decay channel $\tilde{\chi}_2^0 \to \nu\tilde{\nu}$, and effectively turns off the three-body decay. This causes the drop in sensitivity. For still lower values of m_0, the $\tilde{e}$ becomes sufficiently light to appear in decays, and thus some sensitivity to dielectron decays re-appears.

In summary, the two DØ analyses exclude gluinos with mass below 185 GeV/c^2, and exclude gluinos and squarks with equal masses below 267 GeV/c^2.

5.2 SUSY Searches with Photons

The observation by CDF[25] of one event containing two photons, two electromagnetic clusters (one of which is well-identified as an electron) and large $\not\!\!E_T$ caused an upsurge of interest in those SUSY models that predict final states containing pairs of photons, since such an event is difficult to explain within the Standard Model. The SUSY models that predict such events include two broad classes: models with gauge-mediated supersymmetry breaking, and models with radiative decay of neutralinos.[26–31] In the GMSB models, the source of the photons is the decay $\tilde{\chi}_1^0 \to \gamma\tilde{G}$; in the radiative decay models, the source is the decay $\tilde{\chi}_2^0 \to \gamma\tilde{\chi}_1^0$. In both cases, the final state contains one or more photons and $\not\!\!E_T$. Both CDF and DØ have conducted searches for events consistent with such models.

5.2.1 Search for Scalar Top with Radiative Neutralino Decay

CDF has performed an analysis searching for the production and decay of charginos and neutralinos in a model which includes a light scalar top quark $\tilde{t}_1$; this model was proposed[28] to explain the CDF $ee\gamma\gamma\not\!\!E_T$ event. These models specify $m_{\tilde{\chi}_1^\pm} = 40$ GeV/c^2, $m_{\tilde{\chi}_2^0} = 70$ GeV/c^2, $m_{\tilde{t}_1} = 60$ GeV/c^2, $m_{\tilde{g}} = 225$ GeV/c^2, and $m_{\tilde{q}} = 220$ GeV/c^2 (for $q \neq t$).

Based on such a model, CDF has searched for the production and decay $\tilde{\chi}_i\tilde{\chi}_2^0 \to (\tilde{t}_1 b)(\tilde{\chi}_1^0\gamma) \to (c\tilde{\chi}_1^0 b)(\tilde{\chi}_1^0\gamma)$, where $i = 1$ or 2. The analysis considered both direct

production and the cascade decays of gluinos and squarks. Initial event selection required a photon with $E_T > 25$ GeV, a displaced vertex (indicating the decay of a b-quark) observed in the Silicon Vertex Detector, and $\not\!\!E_T > 20$ GeV; 98 events meeting these criteria were observed in the data. A total of $77 \pm 23 \pm 20$ events was expected from all SM sources, including production of a b quark in association with a jet that is misidentified as a photon (60%), photon + $b\bar{b}$ or $c\bar{c}$ (27%), and direct photon production with an erroneous displaced vertex identification (13%).

Final event selection consisted of raising the $\not\!\!E_T$ threshold to 40 GeV. Two events remained in the data; a background calculation has not been completed. Since no significant number of events was observed, this result was used (without background subtraction) to set an upper limit (at the 95% confidence level) of 6.4 events on number of events expected from the $\tilde{\chi}_i\tilde{\chi}_2^0$ signature. The suggested model predicts 6.7 events in 85 pb^{-1}, and is thus ruled out at slightly more than the 95% confidence level, as is any similar model with a lighter $\tilde{t}_1$.

5.2.2 Search for $\gamma\gamma\not\!\!E_T$

Using a data sample with an integrated luminosity of 106 pb^{-1}, DØ has performed an inclusive search for events with two photons and significant $\not\!\!E_T$. This search neither required nor vetoed extra jets or leptons, and is thus sensitive to models with radiative neutralino decay and to GMSB models. The SM backgrounds to this final state include direct photon production, with one jet misidentified as a photon, and mismeasured $\not\!\!E_T$; $W \to e\nu$ production in association with a single jet, in which the electron track is missed (resulting in its misidentification as a photon) and one jet is misidentified as a photon; and $t\bar{t} \to eejj + \not\!\!E_T$ events, in which both electrons are misidentified as photons.

Initial event selection required two electromagnetic clusters in the calorimeter, the first with $E_T > 20$ GeV, and the second with $E_T > 12$ GeV, both in the range $|\eta| < 1.1$ or $1.5 < |\eta| < 2.0$; 229 events were observed in the data. This sample included events with electrons as well as photons. The $\not\!\!E_T$ distribution for these events agreed well with SM expectations, as is seen in Fig. 6.

The final event selection consisted of photon verification (requiring no track and no significant number of tracking chamber hits in the vicinity of the electromagnetic clusters) and the requirement $\not\!\!E_T > 25$ GeV. Two events were observed in the data, with an expected 2.3 ± 0.9 from all SM sources. This result was used

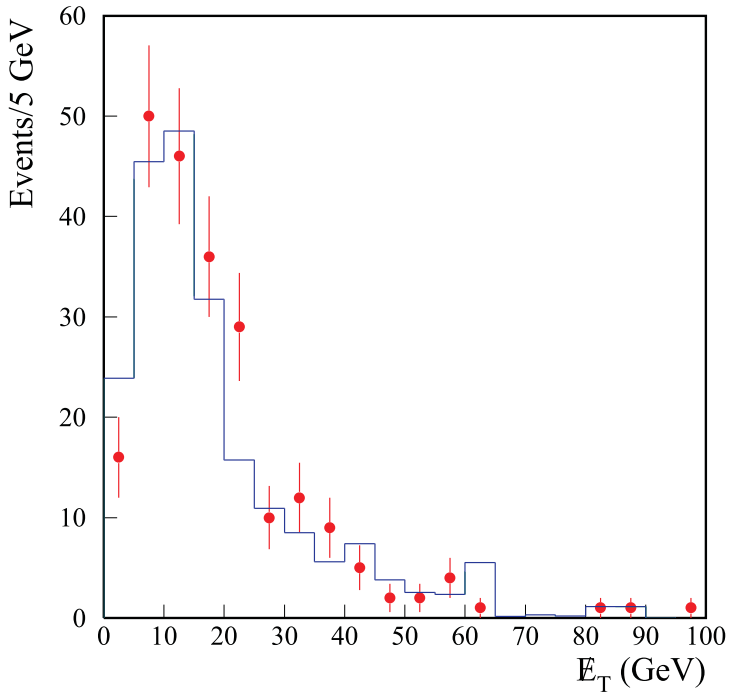

Fig. 6. The $\not{E}_T$ spectrum for events passing the initial event selection in the DØ diphoton + $\not{E}_T$ analysis, compared with the expectation from Standard Model sources. The dots represent the data, and the histogram represents the SM expectation.

to set an upper limit (at the 95% confidence level) on the cross section for chargino and neutralino production, in both GMSB and radiative neutralino decay models.

For the GMSB comparison, the model used was less restrictive than MLES. This model assumes electroweak unification but does not assume grand unification. To describe the phenomenology of the chargino and neutralino sectors, it requires the specification of three parameters: M_2 (a mass associated with the $SU(2)_L$ gaugino; this value also determines M_1, the mass associated with the $U(1)$ gaugino); and two of the same parameters as in MLES models, μ and $\tan\beta$. Unlike MLES models, both the magnitude and sign of μ are free. With the assumption that the sleptons, squarks, and gluinos are heavy enough not to occur in the decay of the $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$, these parameters suffice to describe the phenomenology of the $\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_2^0$, and $\tilde{\chi}_1^0$.

For GMSB models, this limit was expressed as an exclusion contour in (M_2, μ) parameter space; the excluded region is shown in Fig. 7. This analysis excludes $\tilde{\chi}_1^{\pm}$ with mass less than 156 GeV/c^2, and $\tilde{\chi}_1^0$ with mass less than 79 GeV/c^2,

both at the 95% confidence level. The excluded region includes the entire region occupied by the GMSB model proposed to explain the CDF event. For radiative neutralino decay models, the result can be expressed as a cross section limit for $\tilde{\nu}\tilde{\bar{\nu}}$ production, $\tilde{e}\tilde{\bar{e}}$ production, or $\tilde{\chi}_2^0\tilde{\chi}_2^0$ production. The cross section limits are also shown in Fig. 7.

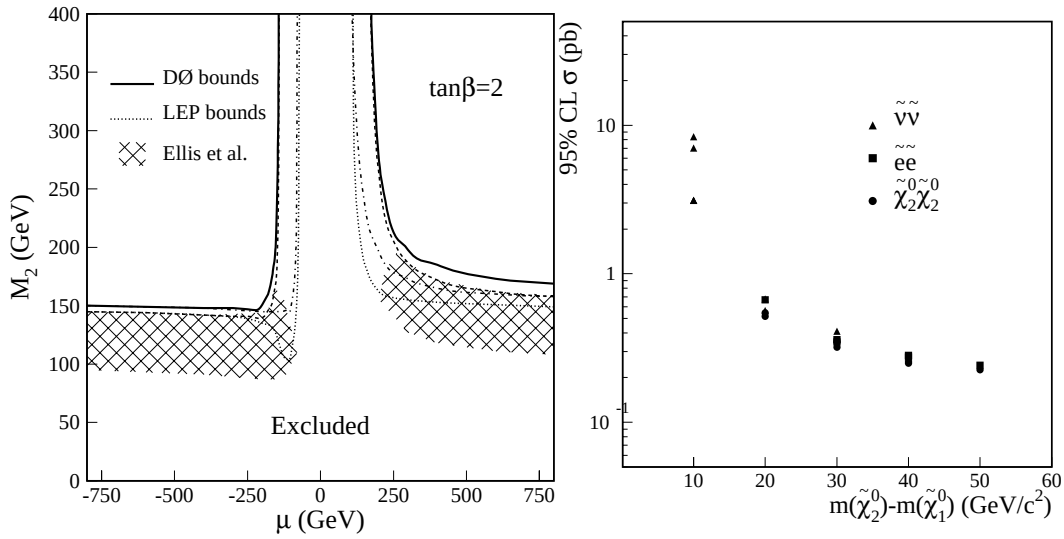

Fig. 7. Left: The exclusion contour in the (M_2, μ) parameter plane for gauge-mediated supersymmetry breaking models, from the DØ diphoton + $\not\!\!E_T$ analysis. The region below the uppermost lines is excluded at the 95% confidence level. Also shown are the regions excluded by the LEP experiments, as well as the region occupied by the GMSB model proposed to explain the $ee\gamma\gamma\not\!\!E_T$ observed by CDF. Right: The upper limit (at the 95% confidence level) on the cross section for various sparticle pair production mechanisms in radiative neutralino decay models, as a function of the mass difference between $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$, resulting from the DØ diphoton + $\not\!\!E_T$ analysis.

5.3 R-Parity Violating SUSY Searches

The excess of high-Q^2 events in e^+p collisions observed by the H1 and ZEUS Collaborations (as mentioned in Sec. 4.1) could be an indication of a squark resonance interacting via R_P-violating coupling $e^+d \xrightarrow{\not{R}} \tilde{c}_L \xrightarrow{\not{R}} e^+d$, where $\xrightarrow{\not{R}}$ indicates a process that does not conserve R_P.[32,33] Such a model violates lepton number conservation, but not baryon number conservation, and therefore, does not predict

proton decay. In such models, the charm squark $\tilde{c}_L$ may also have R_P-conserving decays, which may be predominant. Additionally, because of the presence of R_P-violating interactions, the lightest sparticle need not be stable, and thus, it may carry electric charge or color. In the references noted, two MSSM variants have been proposed to explain the HERA excess. Both models share a similar particle spectrum, with the difference between the two being the identification of the LSP: either $\tilde{c}_L$ or $\tilde{\chi}_1^0$.

Each model specifies $\tan\beta = 2$, $m_{\tilde{\chi}_1^\pm} > m_{\tilde{c}_L}$, ${m_{\tilde{s}_L}}^2 = {m_{\tilde{c}_L}}^2 - {m_c}^2 + {m_s}^2 - {m_W}^2 \cos 2\beta$, and all u- and d-type squarks degenerate, with mass $m_{\tilde{q}}$.

Such a model predicts signatures which should be observable at the Tevatron. If the LSP is $\tilde{c}_L$, then one such signal is gluino pair production and decay $p\bar{p} \to \tilde{g}\tilde{g} \to (\bar{c}\tilde{c}_L)(\bar{c}\tilde{c}_L) \xrightarrow{\not{R}} \bar{c}(e^+d)\bar{c}(e^+d)$, and the charge conjugate. The Majorana nature of the gluino allows decay products with same-sign dileptons 50% of the time. If the LSP is $\tilde{\chi}_1^0$, then the interesting signal is $\tilde{c}_L$ production: $p\bar{p} \to \tilde{c}_L\bar{\tilde{c}}_L \to (c\tilde{\chi}_1^0)(\bar{c}\tilde{\chi}_1^0) \xrightarrow{\not{R}} c(\bar{q}q'e^\pm)\bar{c}(\bar{q}q'e^\pm)$. In this process, it is the Majorana nature of the neutralino that allows the same-sign dilepton signature. In contrast with R-parity conserving supersymmetry signals, these signatures do not contain $\not{E}_T$. The cross section to produce such events from SM sources is very small.

Using a data sample corresponding to an integrated luminosity of 105 pb^{-1}, CDF has searched for events with like-sign electrons and two jets, consistent with the models above. Initial event selection required two electrons with $E_T > 15$ GeV and two or more jets with $E_T > 15$ GeV, with $|\eta(e_1)| < 1.1$ and $|\eta(e_2)| < 2.5$. The requirement that the distance between the points at which the electron tracks intercepted the beam axis be less than 10 cm was used to ensure that both leptons originated from the same interaction, and the $\not{E}_T$ significance requirement was used to veto events with $\not{E}_T$ resulting from the mismeasurement of jets.

The SM contributions to this signature come from heavy quark production and subsequent cascade decays. Preliminary calculations of $t\bar{t}$ and b/c-quark production rates have been performed, yielding a predicted 1.2 ± 0.2 (statistical error only) opposite-sign ee events. One such event is observed with $\not{E}_T$ significance of 10.1; this event is lost to the sample due to the $\not{E}_T$ significance cut at 5.0. At the 95% confidence level, fewer than 0.09 events with like-sign dileptons are expected from $t\bar{t}$ production and decay. More difficult to estimate is the expected number of events from b- and c-quark production, either through direct production or

from gluon splitting in initial- or final-state radiation. A preliminary upper limit of 9.5 events was expected, at the 95% confidence level.

This result was used to set upper limits on the cross section for both $\tilde{g}\tilde{g} \xrightarrow{\not{R}} \ell^{\pm}\ell^{\pm} + 2j$ and $\tilde{c}_L\bar{\tilde{c}}_L \xrightarrow{\not{R}} \ell^{\pm}\ell^{\pm} + 2j$. The regions of MSSM parameter space excluded in the context of the two models are shown in Fig. 8.

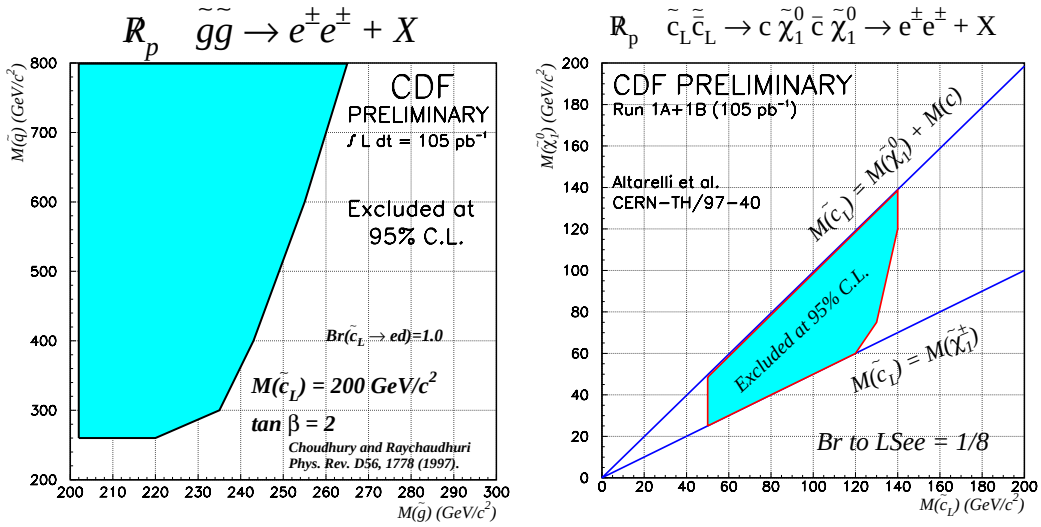

Fig. 8. Left: The exclusion contour in the $(m_{\tilde{g}}, m_{\tilde{q}})$ mass plane from the CDF like-sign dilepton analysis, in the framework of the $\tilde{g}\tilde{g} \xrightarrow{\not{R}} \ell^{\pm}\ell^{\pm} + 2j$ model. The shaded region is excluded at the 95% confidence level. Right: The exclusion contour in the $(m_{\tilde{c}_L}, m_{\tilde{\chi}_1^0})$ mass plane from the CDF like-sign dilepton analysis, in the framework of the $\tilde{c}_L\bar{\tilde{c}}_L \xrightarrow{\not{R}} \ell^{\pm}\ell^{\pm} + 2j$ model. The shaded region is excluded at the 95% confidence level.

6 Conclusion

The Standard Model remains a successful description of elementary particle physics. Thus far we have observed no evidence of phenomena beyond the predictions of the SM. Nonetheless, theories which go beyond the SM have attractive features that make their investigation important. The current data sample (~ 100 pb^{-1}, for each of the two experiments) has provided excellent opportunities to investigate many such theories, and has provided a fertile base for analyses which probe such theories to a degree previously unachievable.

In the year 2000, the CDF and DØ experiments will begin a new round of data collection, with a Tevatron upgraded to $\sqrt{s} = 2$ TeV, delivering beam to the two upgraded detectors. The next run will deliver an integrated luminosity of 2–4 fb^{-1} to each detector, a factor of 20 greater than the previous run. Both experiments are currently preparing for this Run II, which will provide an excellent opportunity to observe the remaining undiscovered member of the SM particle spectrum—the Higgs boson—or, perhaps, something unexpected.

References

[1] W. J. Thompson, "Introduction to Colliding Beams at Fermilab," FERMILAB-TM-1909, 1994.

[2] F. Abe *et al.* (CDF Collaboration), Nucl. Instrum. Methods A **271**, 387 (1988).

[3] F. Abe *et al.* (CDF Collaboration), Phys. Rev. D **50**, 2966 (1994).

[4] S. Abachi *et al.* (DØ Collaboration), Nucl. Instrum. Methods A **338**, 185 (1994).

[5] The LEP Collaborations, the LEP Electroweak Working Group, and the SLD Heavy Flavour Group, CERN-PPE/97-154.

[6] J. Pati and A. Salam, Phys. Rev. D **10**, 275 (1974).

[7] E. Eichten *et al.*, Phys. Rev. Lett. **50**, 811 (1983).

[8] J. L. Hewett and T. G. Rizzo, Phys. Rep. **183**, 193 (1989).

[9] M. Leurer, Phys. Rev. D **49**, 333 (1994).

[10] M. Derrick *et al.*, Z. Physik C **73**, 613 (1997).

[11] S. Aid *et al.* (H1 Collaboration), Phys. Lett. B **369**, 173 (1996).

[12] C. Adloff *et al.* (H1 Collaboration), Z. Phys. C **74**, 191 (1997).

[13] J. Breitweg *et al.* (ZEUS Collaboration), Z. Phys. C **74**, 207 (1997).

[14] N. Amos *et al., Proceedings of the International Conference on Computing in High Energy Physics*, **95**, 215 (1996).

[15] Yu. A. Golfand and E. P. Likhtman, JETP Lett. **13**, 452 (1971); D. Volkov and V. P. Akulov, JETP Lett. **16**, 438 (1972).

[16] J. Wess and B. Zumino, Nucl. Phys. B **78**, 1 (1974).

[17] H. Georgi and S. L. Glashow, Phys. Rev. Lett. **32**, 438 (1974).

[18] E. Gildener, Phys. Rev. D **14**, 1667 (1976).

[19] S. Dimopoulos and H. Georgi, Nucl. Phys. B **193**, 150 (1981).

[20] S. Dimopoulos *et al.*, Phys. Rev. D **24**, 1681 (1981).

[21] N. Sakai, Z. Phys. C **11**, 153 (1981).

[22] J. Ellis *et al.*, Nucl. Phys. B **238**, 453 (1984).

[23] S. Abachi *et al.* (DØ Collaboration), Phys. Rev. Lett. **75**, 618 (1995).

[24] F. Abe *et al.* (CDF Collaboration), Phys. Rev. D Rapid Communications, **56**, R1357 (1997).

[25] D. Toback, FERMILAB-Conf-96/240-E (1996).

[26] H. Haber *et al.*, Phys. Lett. B **160**, 297 (1985).

[27] S. Dimopoulos *et al.*, Phys. Rev. Lett. **76**, 3494 (1996).

[28] S. Ambrosanio *et al.*, Phys. Rev. Lett. **76**, 3498 (1996).

[29] G. Kane and J. Wells, Phys. Rev. Lett. **76**, 4458 (1996).

[30] K. Babu *et al.*, Phys. Rev. Lett. **77**, 3070 (1996).

[31] J. Lopez and D. Nanopoulos, Mod. Phys. Lett. A **10**, 2473 (1996).

[32] D. Choudhury and S. Raychaudhuri, Phys. Lett. B **401**, 54 (1997).

[33] D. Choudhury and S. Raychaudhuri, Phys. Rev. D **56**, 1778 (1997).