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SEARCHES FOR EXOTICS AT THE TEVATRON

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Abstract

The Fermilab Tevatron collider experiments CDF and DØ collected more than 100 pb^{-1} of data at $\sqrt{s} = 1.8$ TeV during Run I (1992-1995). Results of searches for new phenomena (exotics) are presented, covering supersymmetry, leptoquarks, technicolor, and quark compositeness. In each case, no discrepancy with the Standard Model is observed, and stringent limits on new physics predicted by these models are extracted. Parameters for Run II of the Tevatron are given along with projections of search reaches for this upcoming run.

1 Introduction

While the most important results from Run I of the Fermilab Tevatron collider experiments, CDF and DØ, were the discovery and subsequent measurements of the top quark, much work also has been done by both collaborations in searches for phenomena beyond those predicted by the Standard Model (SM). Motivation for these searches for exotic physics comes from various extensions of the SM.

In Run I (1992-95) the experiments each collected over 100 pb^{-1} of data in $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV. These high-quality data are especially sensitive to exotics involving leptons (primarily e and μ in this run) due to excellent tracking, EM calorimeters, and muon chambers. Strongly-produced exotic processes can also be probed extensively because the cross sections are quite large at the Tevatron. In the following sections we outline recent searches for supersymmetry, leptoquarks, technicolor, and quark compositeness by CDF and DØ in Run I, and sketch plans for the upcoming Run II.

2 SUSY searches

One well-motivated extension to the SM is supersymmetry (SUSY), which relates particles with different spin. 1) This theory introduces a new spectrum of particles: a boson for each SM fermion and vice versa. These SUSY particles (sparticles) contribute to the Higgs[1] mass squared with opposite sign relative to the contributions of SM particles, and thus protect the weak mass scale, $M(W)$ from divergences. SUSY is a broken symmetry since the sparticles obviously do not have the same mass as their SM partners, but the breaking must be "soft" to allow the divergence canceling to remain effective.

The simplest version of SUSY is the Minimal Supersymmetric Standard Model (MSSM) which parameterizes ignorance of the mechanism of SUSY breaking with soft-breaking terms in the superpotential. Its sparticle content is shown in Table 1. Precision electroweak data constrain the size of these terms and therefore the masses of these sparticles. Other variations of SUSY include Minimal Supergravity (mSUGRA) in which SUSY is broken at the unification scale by gravitational interactions, and Gauge Mediated SUSY Breaking (GMSB) in which gauge interactions are responsible for this. In effect, both assume a "hidden" sector at very high energies at which SUSY breaking occurs, and a "visible" sector containing the MSSM

[1] The Higgs boson is the fundamental scalar particle associated with electroweak symmetry breaking (EWSB).

Table 1: *Additional particle states predicted by the MSSM.*

sparticle	spin	symbol
squarks	0	$\tilde{q}_{L,R}$
sleptons	0	$\tilde{\ell}_{L,R}$, $\tilde{\nu}_\ell$
charginos	1/2	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$
neutralinos	1/2	$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$
gluino	1/2	$\tilde{g}$
gravitino	3/2	$\tilde{G}$
Higgs	0	$h, H, A, H^\pm$

sparticles. Some mechanism is then invoked to transmit the SUSY breaking from the hidden to the visible sector.

2.1 DØ search for R-parity violating SUSY using multileptons

The MSSM is constructed to conserve baryon number (B) and lepton number (L) and the requirement of R-parity (R_p) [2] conservation is imposed on the couplings: for a particle of spin S, the multiplicative quantum number $R_p \equiv (-1)^{3B+L+2S}$ distinguishes SM particles ($R_p = +1$) from SUSY particles ($R_p = -1$). If R_p is conserved, SUSY particles can only be produced in pairs and the lightest supersymmetric particle (LSP) is stable. The assumption of R_p conservation thus leads to experimental signatures with appreciable missing transverse energy ($\not\!\!E_T$), provided that the LSP is electrically neutral and colorless. [3] R_p conservation, however, is not required by SUSY theories in general and viable R_p violating ($\not\!R_p$) models can be built by adding explicitly B *or* L violating couplings to the SUSY Lagrangian. [4] Since the LSP can be unstable in this case, the standard $\not\!\!E_T$ signature is diluted.

DØ searches for events with multiple electrons and/or muons, which have low SM backgrounds but can occur at appreciable rates in SUSY models with non-zero λ couplings. The $\not\!R_p$ superpotential includes $\lambda_{ijk}L_iL_j\overline{E}_k$ terms, where Yukawa-type couplings λ with generational indices i, j, k multiply products of lepton and electron superfields (L, E). These couplings allow for the decay of the LSP (taken here to be the lightest neutralino, $\tilde{\chi}_1^0$) to two charged leptons and a neutrino. DØ makes the assumption that only one λ is non-zero at a time, and that it is small enough (typically $0.001 < \lambda < 0.01$) so that $\not\!R_p$ effects make negligible changes to the production and decay of all SUSY sparticles other than the LSP, which then decays violating R_p. Thus every event has at least 2 LSPs that decay, yielding events with

Table 2: DØ *trilepton search results used in* $\not{R}_p$ *SUSY search.*

Channel	$\int \mathcal{L}\, dt(\mathrm{pb}^{-1})$	Background	Observed
eee	94.9 ± 5.0	0.34 ± 0.07	0
$ee\mu$	94.9 ± 5.0	0.61 ± 0.36	0
$e\mu\mu$	89.5 ± 4.7	0.11 ± 0.04	0
$\mu\mu\mu$	75.3 ± 4.0	0.20 ± 0.04	0

≥ 4 leptons and $\not{E}_T$.

The analysis attempts to maximize its sensitivity to such events by, in fact, requiring only three leptons to pass their cuts. Thus DØ uses the analysis from their $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ search [5] and reinterprets its null result as limits on mSUGRA scenarios with non-zero $\not{R}_p$ λ couplings. This analysis requires 3 isolated[2] leptons, ($\ell = e, \mu$), with $0 < |\eta(e)| < 1.2, 1.4 < |\eta(e)| < 3.5$, and $|\eta(\mu)| < 1.0$. [6] Cuts are applied on $E_T(\ell)$, $\not{E}_T$, $\Delta\phi(\ell\ell)$, and $\Delta\phi(\mu\not{E}_T)$ [6] to remove instrumental background sources and cosmic rays. For the eee channel, opposite-sign dielectrons with mass in the Z^0 peak are also removed. The four channels searched along with the results are shown in Table 2.

DØ reinterprets the null result in an mSUGRA framework with $\not{R}_p$ decays of the $\tilde{\chi}_1^0$. The common trilinear coupling A_0 is set to zero; $\tan\beta$, the ratio of the vacuum expectation values for the two Higgs doublets, is examined at both 5 and 10, along with both signs of μ, the higgsino mass parameter. Three λ couplings are considered, with the assumption that only one is nonzero at a time. These couplings and their present experimental limits are $\lambda_{121} < 0.05 \cdot M(\tilde{e}_R^k)/100$ GeV, $\lambda_{122} < 0.05 \cdot M(\tilde{e}_R^k)/100$ GeV, and $\lambda_{233} < 0.06 \cdot M(\tilde{e}_R^k)/100$ GeV. [7] These run through much of the range of sensitivity as detection efficiencies for electrons are high while for taus they are low. A scan is performed in the space of m_0 and $m_{1/2}$, the mSUGRA common scalar and gaugino masses, assuming all allowed sparticle production and decay modes. Typical efficiencies times branching ratios near the limit contours are 20% for λ_{121}, 10% for λ_{122}, and 0.3% for λ_{233}. Results are shown in Figures 1 and 2. For each plot, the various curves are defined as follows. The dashed line indicates the limit of the sensitivity in $m_{1/2}$ for the least favorable case, i.e., for the λ_{233} coupling. The exclusion region corresponds to the area below the

[2]For example, electrons must have less than 10% of their measured energy found in an annular region $0.2 < \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.4$ about their direction.

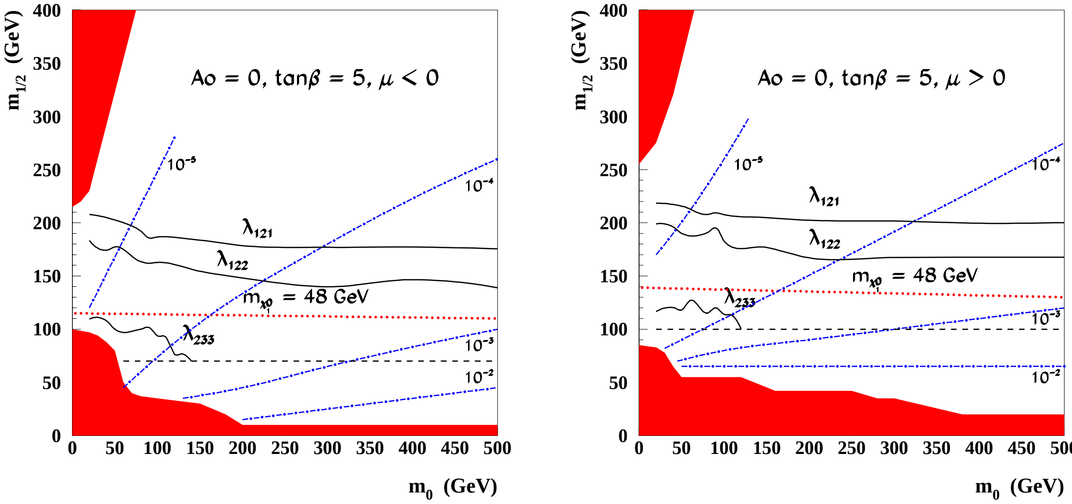

Figure 1: DØ *search for* $\not R_p$ *SUSY in multilepton events. The various curves are explained in the text. Left: results in the mSUGRA mass plane for* $\tan\beta = 5$ *and* $\mu < 0$. *Right: results for* $\tan\beta = 5$ *and* $\mu > 0$.

solid line labelled with the coupling type, and above the higher of the dashed line and the dash-dotted curve specifying the numerical values of λ. In the region above the dash-dotted curves, the average decay length of the LSP calculated for the value of the coupling indicated on the curve, is less than 1 cm. Since efficiency studies for high impact parameter tracks have not been done, the present study is conservatively restricted to decay lengths less than 1 cm. Thus, for example, the region between curves labelled with λ_{121} and 10^{-3} is excluded for $\lambda_{121} > 10^{-3}$. The shaded areas indicate the regions where there is no electroweak symmetry breaking or where the LSP is not the lightest neutralino. Finally, limits corresponding to the present lower limit on the $\tilde{\chi}_1^0$ mass (dotted line), are also shown. [8)]

2.2 CDF search for the top squark in $b + \ell + \not E_T$ events

Due to the heavy top mass and large predicted mixing in the third generation of the SUSY spectrum, the lighter top squark, $\tilde{t}_1$, may be among the lightest SUSY sparticles. Since it is also pair-produced with large cross sections in $p\overline{p}$ collisions, it is an excellent search candidate at the Tevatron. CDF searches for such squarks in 88 pb^{-1} of data assuming R_p conservation and that $M(\tilde{t}_1) < M(t)$. Two complementary decays of the top squark are examined: $Br(\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}) = 100\%$ with $\tilde{\chi}_1^{\pm} \to e\nu\tilde{\chi}_1^0$ or $\tilde{\chi}_1^{\pm} \to \mu\nu\tilde{\chi}_1^0$ (each with $Br = 11\%$), and $Br(\tilde{t}_1 \to b\ell\tilde{\nu}) = 100\%$ with $Br = 1/3$ for

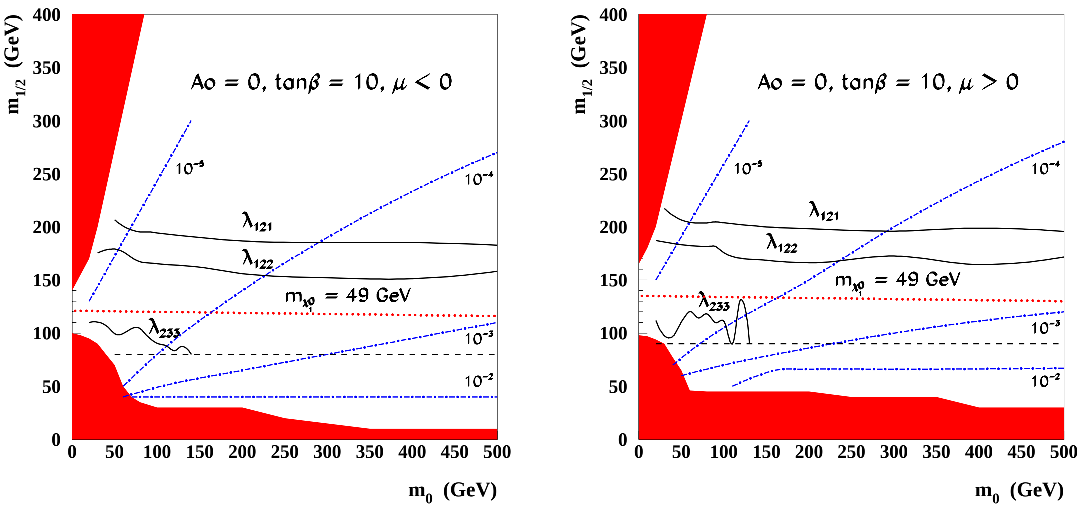

Figure 2: DØ *search for* $R\!\!\!/_p$ *SUSY in multilepton events. The various curves are explained in the text. Left: results in the mSUGRA mass plane for* $\tan\beta = 10$ *and* $\mu < 0$. *Right: results for* $\tan\beta = 10$ *and* $\mu > 0$.

each e, μ, and τ. For both cases, the event signature is b-tag + lepton + $\not\!\!E_T$.

Events are selected that contain at least one electron or muon with $p_T >$ 10 GeV/c; 2 or more jets with $E_T(j_1) > 12$ GeV and $E_T(j_2) > 8$ GeV; $\not\!\!E_T > 25$ GeV; $\Delta\phi(\not\!\!E_T, j) > 0.5$; and at least one b-tag from the SVX detector information. The SM background to this selection, predominantly from $W + jets$, $t\bar{t}$, and processes with jets that are misidentified as leptons, is predicted to contribute 86.2 ± 5.2 events while 81 are observed in the data. Given this good agreement, limits are extracted for this model.

For the case of $\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$ a two parameter likelihood fit is used to determine a possible top squark contribution in the data. The backgrounds, data, and fit results are shown in Figure 3 for the variables $H_T \equiv \sum E_T$ and $\Delta\phi(jet1, jet2)$, for the case $M(\tilde{t}_1) = 100$ GeV/c^2, $M(\tilde{\chi}_1^{\pm}) = 90$ GeV/c^2, and $M(\tilde{\chi}_1^0) = 40$ GeV/c^2. The fit is consistent with zero stop contribution, and the resulting cross section limit is shown in Figure 3. There is about a factor of 5 between the limit and the expected cross section. However, this mode will have useful sensitivity in Run II of the Tevatron during which at least 20 times more data will be taken with improved detectors.

The second decay of the top squark, $\tilde{t}_1 \to b\ell\tilde{\nu}$, dominates if the $\tilde{\nu}$ is light and $\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$ is not kinematically allowed. For this analysis, a fit to the H_T spectrum is performed. The result is again consistent with 0 stop events, but in this case the cross section times branching ratio limits are much lower as shown in Figure 4.

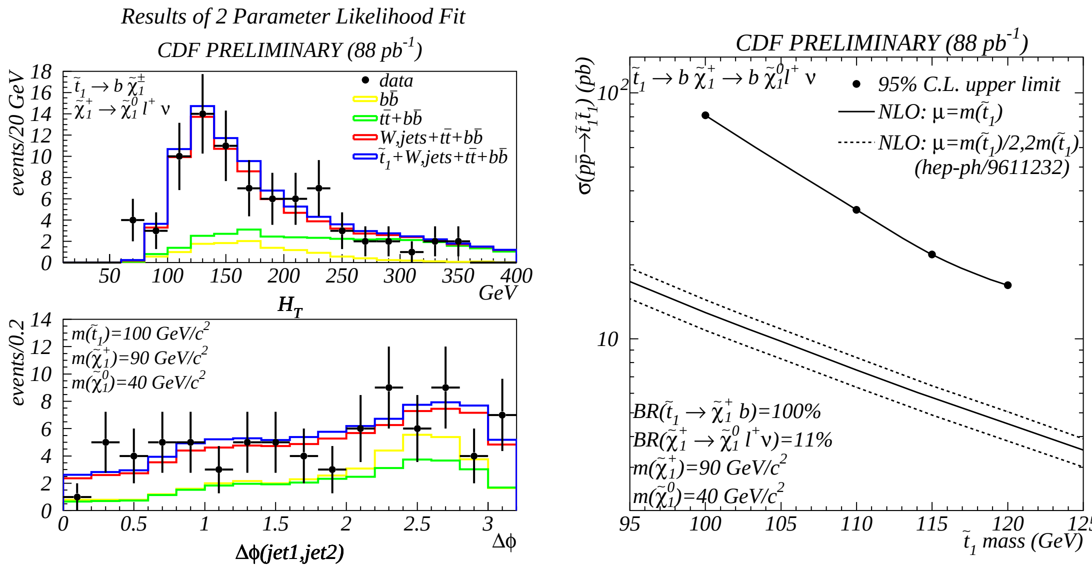

Figure 3: *CDF search for $b + \ell + \not\!\!E_T$ events and resulting limits on the stop squark. Left: results of a likelihood fit to H_T and $\Delta\phi(j1, j2)$. Right: Cross section limit for the case in which $Br(\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}) = 100\%$.*

This is due to the larger branching ratios to leptons and their harder p_T spectra. This allows mass limits to be set, in the $M(\tilde{t}_1)$-$M(\tilde{\nu})$ plane, as shown in Figure 4. Maximum exclusion is achieved for $M(\tilde{t}_1) = 110$ GeV$/c^2$ and $M(\tilde{\nu}) = 50$ GeV$/c^2$.

3 CDF search for leptoquarks and technicolor in $\not\!\!E_T$ + heavy flavor jet events

Various extensions to the SM, including grand unified theories, introduce new particles that have both lepton and quark quantum numbers. These leptoquarks [9] (LQ) are color-triplet bosons with spin 0 or 1 and fractional electric charge. If B and L are separately conserved then their masses can be accessible at present collider energies. At the Tevatron, LQs are pair-produced in quark-antiquark annihilation and gluon-gluon fusion with cross sections that are nearly independent of the Yukawa type couplings between the LQs and their decay lepton-quark pairs.

As LQs decay to a lepton plus a quark, pair-produced LQs give signatures of $\ell\ell + jets$, $\ell\nu + jets$, and $\nu\nu + jets$, with rates proportional to β^2, $2\beta(1-\beta)$, and $(1-\beta)^2$, respectively, where β is the branching ratio of a LQ decaying to a charged lepton plus a jet. CDF and DØ have several LQ results from Run I (summarized in Ref. [9]); here we report on a new CDF search for scalar and vector second and third generation LQs for the case $\beta = 0$. [10] The signature for these events is heavy

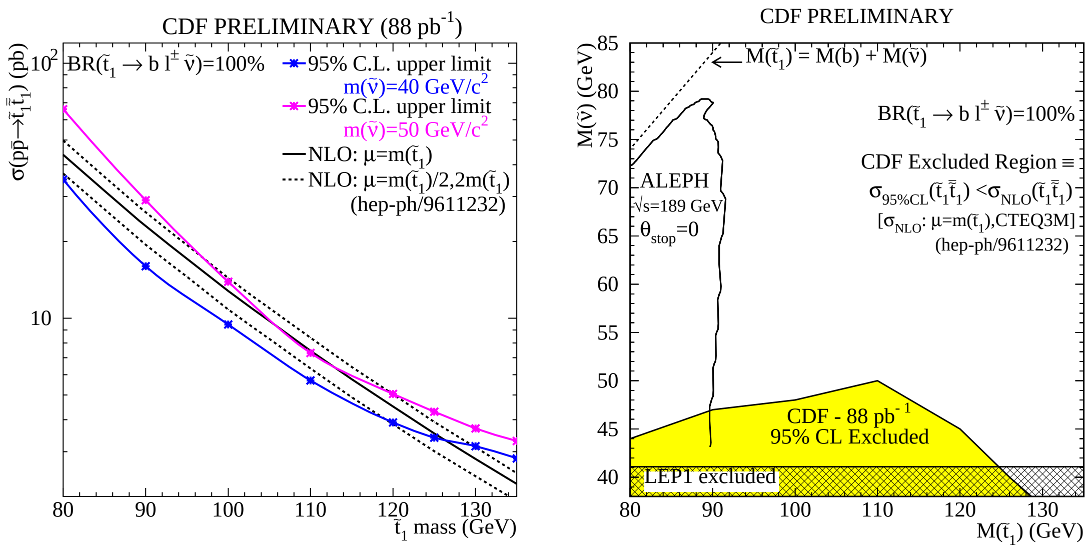

Figure 4: *CDF search for $b + \ell + \not\!\!E_T$ events and resulting limits on the stop squark. Left: cross section times branching ratio limits for the case $\tilde{t}_1 \to b\ell\tilde{\nu}$. Right: exclusion in the $M(\tilde{t}_1)$-$M(\tilde{\nu})$ plane.*

flavor jets, identified with information from the SVX detector, plus appreciable $\not\!\!E_T$.

CDF examines two LQ scenarios: 1) continuum LQs are pair-produced and decay $LQ2 \to c\nu_\mu$ and $LQ3 \to b\nu_\tau$, where the LQs are either scalar or vector; and 2) resonant Technicolor LQs. Here, a color-octet technirho (ρ_{T8}) is produced as a resonance in $p\overline{p}$ collisions, and can decay as $\rho_{T8} \to \pi_{T3}\pi_{T3}$. This color-triplet technipion acts as a LQ, and in turn decays as $\pi_{T3} \equiv \pi_{LQ} \to b\nu_\tau$ or $\pi_{T3} \equiv \pi_{LQ} \to c\nu_\tau$. This second decay is possible if $M(\pi_{LQ}) < M(t)$; otherwise the decay is $\pi_{LQ} \to t\nu_\tau$.

In both cases, the signature is b or c jets plus $\not\!\!E_T$. This search is performed using data sets and analysis techniques employed in CDF's search for the FCNC decay of the stop squark $\tilde{t}_1 \to c\tilde{\chi}^0_1$ and the decay $\tilde{b}_1 \to b\tilde{\chi}^0_1$ [11]. Here we summarize the data analysis. Data are taken with online triggers that require large missing transverse energy, $\not\!\!E_T > 35$ GeV. After removing accelerator and cosmic ray sources of $\not\!\!E_T$, 300K events remain. These are dominated by QCD backgrounds, which are reduced by requiring 2 or 3 hard jets: $E_T(j) > 15$ GeV with $|\eta(j)| < 2$ and by vetoing events with 7 GeV $< E_T(j) <$ 15 GeV for $|\eta| < 3.6$. Fake sources of $\not\!\!E_T$ are removed by increasing the cut to $\not\!\!E_T > 40$ GeV and by applying angular restrictions to further reduce $\not\!\!E_T$ from energy mismeasurement: $\Delta\phi(\not\!\!E_T, j) > 45^0$, $\Delta\phi(\not\!\!E_T, j_1) < 165^0$, and $\Delta\phi(j_1, j_2) < 165^0$. At this stage 569 events remain. Next, W and Z^0 backgrounds are reduced by vetoing events with high p_T e's or μ's, leaving 396 events.

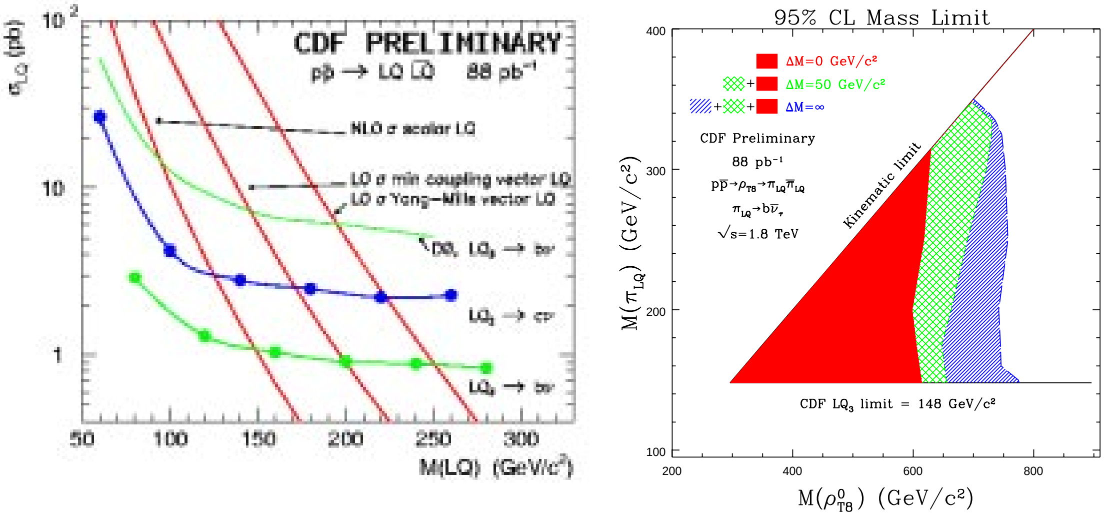

Figure 5: *CDF search for leptoquarks in* $\not\!\!E_T$ *plus heavy flavor jet events. Left: continuum leptoquark limits for LQ2 and LQ3. Right: resonant (technicolor) leptoquark limits for the case* $Br(\pi_{LQ} \to b\nu) = 100\%$.

Finally, heavy flavor jets are identified using SVX information. Using impact parameter information and resolution, a jet probability (JP) algorithm calculates the combined probability that tracks that form a jet originate from the primary vertex. Thus light flavor, or prompt, jets have JP near 1, while b and c jets have JP peaked near zero. For the $LQ2(LQ3)$ analysis, at least 1 jet with $JP < 5\%(JP < 1\%)$ is required with a signal efficiency of 25%(45%). The remaining background is dominated by $W+1j$ events with $W \to \tau\nu$ and the τ decaying hadronically. For the $LQ2(LQ3)$ analysis, $14.5 \pm 4.2(5.8 \pm 1.8)$ events are expected from SM backgrounds, and 11(8) events are observed. Given this good agreement, limits are set on scalar and vector continuum LQs (for scalar LQs: $M(LQ2) > 123$ GeV/c^2 and $M(LQ3) > 148$ GeV/c^2 at 95% C.L.) and on technicolor LQs (Figure 5). Note that for the technicolor LQ analysis, the additional exclusion over that from the continuum LQ limits depends on a parameter $\Delta M \equiv M(\pi_{T8}) - M(\pi_{T3})$. The color-octet technipion, π_{T8}, is another possible decay product of the ρ_{T8} but does not lead to the heavy flavor plus $\not\!\!E_T$ signature; this case has been studied in a previous search by CDF. [12)]

4 DØ search for quark compositeness

The search for quark compositeness and contact terms is natural in the hadron collider environment since by testing perturbative QCD at high energies (corresponding to distance scales down to 10^{-19} m) knowledge of the parton content of the proton and the nature of the strong interaction is gained [13].

DØ searches for quark compositeness by considering the event scalar sum of jet E_T: $H_T \equiv \sum_{i=1}^{N} {E_T}^i$, where N is number of jets above some threshold. [14] H_T is a robust quantity as overlapping events contribute a small and correctable bias. Moreover, this method treats the event as a whole and therefore complements previous Tevatron searches ($d\sigma/dE_T$, $M(jj)$, and dijet angular distributions). [13] DØ follows the formalism of Eichten *et al.* [15] and searches in the regime of $H_T >$ 500 GeV for compositeness of the q_L in an L-L isoscalar term:

$$A(g^2/2\Lambda_{LL}^2)\bar{q_L}\gamma^\mu q_L\, \bar{q_L}\gamma_\mu q_L \tag{1}$$

where $A = \pm 1$, Λ_{LL} is the compositeness scale, and g^2 is the compositeness coupling constant.

Data are taken with a trigger requiring $E_T > 45$ GeV in a calorimeter region $\Delta\eta \times \Delta\phi = 0.8 \times 1.6$. Beam halo from the Main Ring[3] is minimized with timing restrictions. Offline, events are selected with ≥ 1 jet with $E_T > 115$ GeV and $H_T > 500$ GeV. Events with multiple primary vertices are the only background to this selection, and are reduced as follows: the two vertices with the largest track multiplicities are kept, and for each the quantity $\not{E}_T \equiv \left|\sum_{i=1}^{N} \vec{E_T}^i\right|$ is calculated. The vertex with smaller $\not{E}_T$ is then kept. H_T is calculated for jets with $E_T > 20$ GeV and $|\eta| < 3.0$. The resulting $d\sigma/dH_T$ spectrum has the expected exponentially falling distribution.

The JETRAD [16] (NLO) calculation is used for the SM H_T spectrum while PYTHIA [17] is used to simulate compositeness to LO. DØ performs a scan in the renormalization scale μ: $\mu = f_E \cdot {E_T}^{max}$ and $\mu = f_H \cdot H_T$, with f_E and f_H in the range from 0.25 to 1.5, noting that changes in μ affect the cross section and not the shape of the spectrum. PDFs CTEQ4M and MRST are examined. Monte Carlo events are smeared according to DØ measured resolution functions (independent of H_T) and corrected for the jet energy scale. Systematic uncertainties for this analysis range from 17% to 34%, and are highly correlated in H_T.

The comparison of the data to the JETRAD prediction is shown in Figure 6 and shows good agreement. Using the PYTHIA simulation, DØ proceeds to set lower limits at 95% C.L. on the compositeness scale: $\Lambda_{LL} > 1.9 - 2.2$ TeV as a function of A, f_E, and f_H. A slight increase in the limit is reported for $A = -1$ and the MRST PDFs. The resolving power for this high-energy microscope is thus

[3] The Main Ring is the Run I Tevatron preaccelerator.

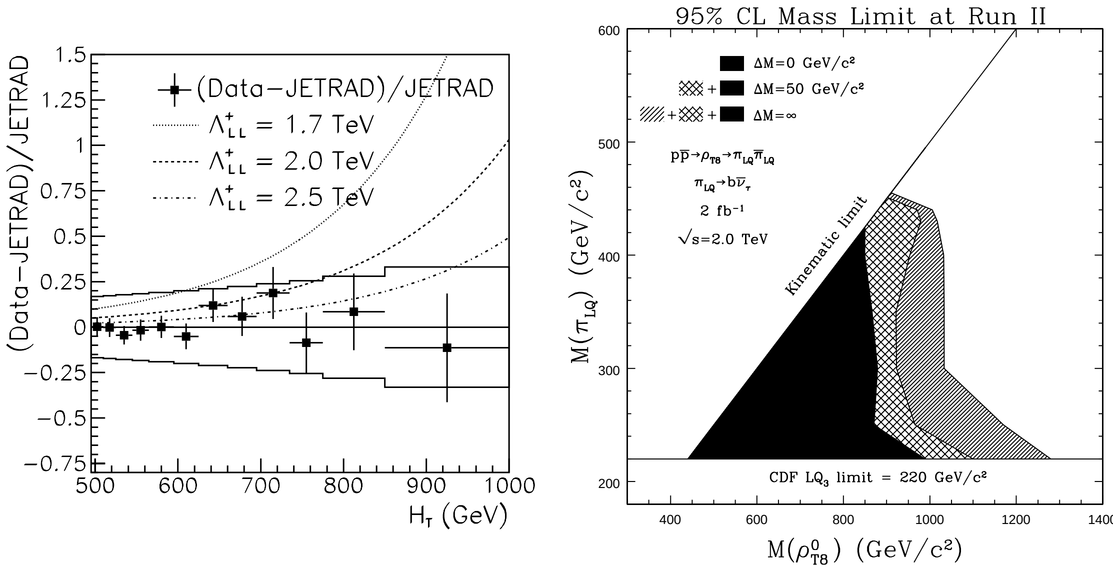

Figure 6: *Left:* DØ *search for quark compositeness in events with large H_T. Right: Projected technicolor leptoquark reach in Run II with $\int \mathcal{L}\, dt = 2$ fb^{-1}.*

$\Delta x \sim \hbar c/\Lambda_{LL} \sim 1 \times 10^{-4}$ fm. If quark compositeness does indeed exist, it must be at a smaller distance scale than this.

5 Run II prospects

Run II of the Tevatron is slated to begin in 2001 with a higher center of mass energy ($\sqrt{s}$ = 2.0 TeV), higher instantaneous luminosity (2×10^{32} cm^{-2}s^{-1}), and much more integrated luminosity ($2 - 30$ fb^{-1}/experiment) than in Run I. To take full advantage of these substantial collider improvements, the CDF and DØ detectors are also undergoing major upgrades. CDF in Run II will employ a new silicon tracker, drift chamber, calorimeter, muon chambers, triggers, and data acquisition system; DØ will have a new magnet, silicon detector, drift chamber, muon chambers, triggers, and data acquisition system. These enhancements compound the effects on exotics searches of the sizable increase in statistics provided by the Tevatron upgrade. [18] A simple projection of the CDF search for technicolor leptoquarks decaying to $b\nu_\tau$ in Run II with $\int \mathcal{L}\, dt = 2$ fb^{-1} is given in Figure 6. Exclusions to 1 TeV/c^2 and beyond in the technirho mass will be attainable. Similarly for various SUSY, leptoquark, and other exotics scenarios, this reach also indicates that the discovery potential in Run II will be substantial.

6 Conclusion

We present CDF and DØ searches for exotics using data taken during Run I of the Tevatron. In each case, excellent agreement with SM predictions is seen and limits on SUSY (with and without R_p violation), leptoquarks, technicolor, and quark compositeness are set. Run II will begin in 2001 and the two experiments, operating with improved detectors, will collect 20-300 times more data at $\sqrt{s} = 2.0$ TeV. This run offers a real window for discovery of new physics before the turn-on of the LHC.

7 Acknowledgements

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