SEARCHES FOR NEW PHYSICS AT THE TEVATRON

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This paper summarizes searches at the Fermilab Tevatron for a wide variety of signatures for physics beyond the Standard Model. These include searches for supersymmetric particles, in the two collider detectors and in one fixed target experiment. Also covered are searches for leptoquarks, dijet resonances, heavy gauge bosons, and particles from a fourth generation, as well as searches for deviations from the Standard Model predictions in dijet angular distributions, dilepton mass distributions, and trilinear gauge boson couplings.

1 Introduction

The wide variety of models which predict physics different from the extremely successful Standard Model can be divided into two types: theories which propose new symmetries (such as supersymmetry and grand unified theories) and theories which propose new dynamics (such as technicolor in all its variations and theories of compositeness in the Standard Model's elementary building blocks). Often the two types can predict the same kind of new particle or effect (leptoquarks, for example, can appear in both types, although perhaps with somewhat different phenomenology). Most relevant for the current paper, however, is the observation that almost all variations of such theories predict signatures for the new physics which are potentially within reach at the center-of-mass energy of the current Tevatron. This paper discusses the searches performed so far for such new physics, and the prospects for future searches, at the Tevatron.

2 Searches for Supersymmetry

2.1 Phenomenology of Supersymmetry at the Tevatron

Supersymmetry relates bosons to fermions, and its existence as a good symmetry at a high mass scale requires the existence of a set of particles which are partners of their Standard Model counterparts, with the same couplings but with different spin and R-parity. (R-parity is a new multiplicative quantum number assigned so that the particles of the Standard Model have R-parity = +1, while their supersymmetric partners have R-parity = −1.) The breaking of supersymmetry at a scale below the unification scale implies that the masses of the superpartners will be different (presumably, higher) than those of ordinary particles. The list of particles and superparticles is given in Table 1. The reader is referred to the reviews in Ref. 1 for discussion of theories of supersymmetry; we discuss here the signatures of supersymmetry which can be seen at the Tevatron.

Table 1: Supersymmetric particle spectrum

R-parity = 1	R-parity = -1	
q	$\tilde{q}_R, \tilde{q}_L$	squarks
l	$\tilde{l}$	sleptons
g	$\tilde{g}$	gluinos
$W^{\pm}$, $H^{\pm}$	$\tilde{\chi}_1^{\pm}$,$\tilde{\chi}_2^{\pm}$	charginos
Z^0,h^0,H^0, A^0,γ	$\tilde{\chi}_1^0$,$\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$,$\tilde{\chi}_4^0$	neutralinos
G	$\tilde{G}$	gravitinos

All the supersymmetry searches reported to date from the Tevatron assume R-parity conservation, which implies that the SUSY particles are produced in pairs, and decay in cascades which must terminate in two LSP's (LSP = lightest supersymmetric particle). In most of the searches, a SUSY model is chosen in which the LSP is the lightest neutralino state $\tilde{\chi}_1^0$. The LSP is constrained to be neutral and non-interacting, so it produces a missing transverse energy ($\not\!\!E_T$) signature in the detectors. The exact particle composition of the decay channels, and hence the branching fractions into various final state topologies, are very dependent on the details of the SUSY model. In calculating acceptance for the various final states, the experiments generally choose simplifying assumptions to limit the model space covered. The most popular simplifying assumptions are derived from supergravity theories.[2]

The top squarks — the supersymmetric partners of the top quark — are a special case for SUSY searches. The large mass of the top quark [3] has the effect in SUSY models of producing different Yukawa couplings for the top squarks which result in a pair of mass eigenstates $\tilde{t_1}$, $\tilde{t_2}$, the lighter of which can be lighter than the top quark itself. The decays of the $\tilde{t_1}$ would be top-like, either to $W + b + LSP$ or to $\tilde{\chi}_1^{\pm} + b$, *unless* these are not kinematically allowed. There is a region in the $m_{\tilde{t_1}}$ vs. m_{LSP} plane, for $\tilde{t_1}$ lighter than $\tilde{\chi}_1^{\pm}$, where the only allowed decay is $\tilde{t_1} \rightarrow c + LSP$, making searches simple and model-independent (although not easy).

We now turn to the specific SUSY searches which have been reported to date from the Tevatron. There are searches for squarks and gluinos (including one from the fixed target program), for charginos and neutralinos, for the lightest top squark, and for the charged Higgs. There is also an investigation of the two-photon + $\not{E}_T$ final state, inspired by models in which radiative decays of the neutralino may play more of a role than in the SUGRA-inspired models commonly used to set limits in the other searches. In some of these models, the gravitino rather than the lightest neutralino is the LSP.

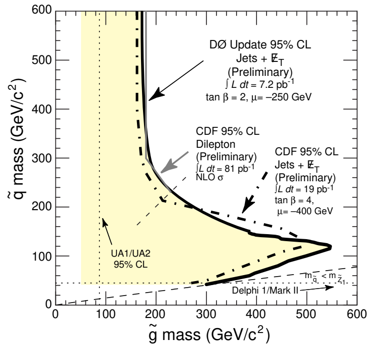


Figure 1: The 95% CL limits in the $m_{\tilde{q}} - m_{\tilde{g}}$ plane from three $\tilde{q}$ -$\tilde{g}$ searches at CDF and DØ.

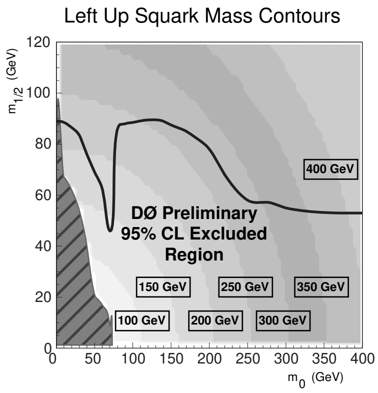


Figure 2: The 95% CL limits in the m_0 - $m_{\frac{1}{2}}$ plane from the DØ dielectron $\tilde{q}$ -$\tilde{g}$ search. The hatched reason is excluded by theoretical constraints.

2.2 Squarks and Gluinos

Squarks and gluinos can be strongly pair-produced at the Tevatron collider, with cross sections for $\tilde{q}$ -$\tilde{\bar{q}}$, $\tilde{g}$ -$\tilde{g}$, and $\tilde{q}$ -$\tilde{g}$ determined in standard QCD calculations, depending on the masses of the new particles. We expect the final states to consist of either multijets + $\not{E}_T$ or jets + leptons + $\not{E}_T$. The $\not{E}_T$ would be due to the existence of two relatively massive LSPs in the final state. Four searches for such pair production have been completed. Both DØ [4] and CDF [5] have searched for the multijet + $\not{E}_T$ final state, and the contours from these searches are shown in Fig. 1. Both these searches use only the data from the 1992-93 Tevatron run, and also use a leading order cross section calculation. Also shown in that figure is the contour from a search by CDF [6] for dileptons + jets + $\not{E}_T$, using the 1992-1995 data, and using an NLO cross section calculation [7] which is ≈ 20 % larger than the LO cross sections. The reach achieved in the dilepton search, with the more favorable cross section and larger luminosity, is comparable to the reach in the hadronic channel over the range where the $\tilde{q}$ mass is larger than the $\tilde{g}$ mass.

DØ has conducted a search for dielectrons + jets + $\not{E}_T$, using the 1994-1995 data, but it is reported within a different model framework than the searches above.[8] This limit was calculated for a consistent supergravity model as a function of m_0 and $m_{\frac{1}{2}}$, with the other SUGRA parameters fixed to be tan $\beta = 2$, $A_0 = 0$, and sgn(μ) = -1, and the result is shown in Fig. 2, in which the limit curve in the m_0 vs. $m_{\frac{1}{2}}$ plane is compared to the mass contours of the $\tilde{q}$. The significant dip in the cross section limit is due to the changing mass relationships — specifically, the limit worsens for m_0 below 100 GeV, when the $\tilde{\nu}$ becomes light enough to provide an invisible decay mode for the $\tilde{\chi}_2^0$, then recovers as the $\tilde{e}$ becomes light enough to provide renewed dielecton modes.

E761, a fixed target experiment designed to study hyperon decays, has also made a search for the expected decays of supersymmetric baryons which would exist in certain theories which call for extremely light gluinos.[9] The theoretical prediction calls for SUSY baryons in a mass range of 1700-2500 MeV, with a lifetime of order 50-500 ps. The limit obtained in the search [10] rules out masses between ≈ 1700 and 2300 MeV, thus substantially limiting but not closing the window available for these light gluino states.

2.3 Charginos and Neutralinos

Two of the lowest mass chargino and neutralino states of the Minimal Supersymmetric Standard Model can be weakly pair produced at the Tevatron: $p\overline{p} \rightarrow \tilde{\chi}_1^{\pm} + \tilde{\chi}_2^0$. The chargino mass region starting just above the existing LEP I limit of approximately 45 GeV (which actually corresponds, in a GUT-inspired MSSM, to a reasonably high gluino mass) is accessible at the Tevatron. The cleanest channels for such a search are the purely leptonic decay channels, where the signature would be three leptons plus $\not{E}_T$. The branching fraction for these channels depends sensitively on the mass of sleptons in the theory, and other parameters. Both DØ and CDF have searched in four channels for this signature: eee, $ee\mu$, $e\mu\mu$, and $\mu\mu\mu$, using the 1994-95 data sample.[11,12] The limit curves obtained are shown in Figs. 3 and 4.

2.4 The Lightest Top Squark

DØ has searched in the 1992-93 data set for the lightest top squark $\tilde{t_1}$, in the topology of two acoplanar jets + $\not{E}_T$.[13] As mentioned above, for certain mass

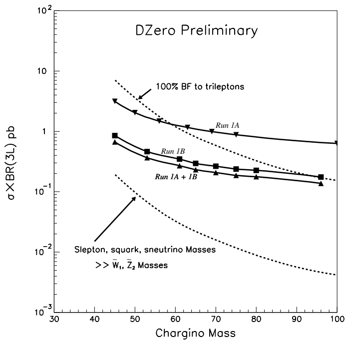


Figure 3: The 95% CL limit on cross section × branching ratio into a single trilepton channel vs. $\tilde{\chi}_1^{\pm}$ mass, from the DØ trilepton search.

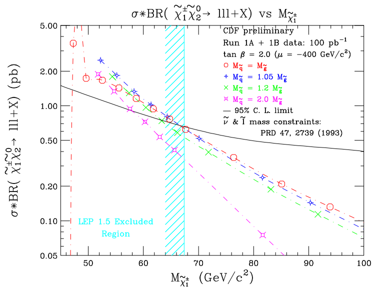


Figure 4: The 95 % limit on cross section × branching ratio into the *four* trilepton channels, from the CDF trilepton search.

regions of the various SUSY particles, this channel is the only kinematically accessible one, and hence the limit is completely model-independent given only that $m_{\tilde{t_1}} < m_{W+b+LSP}$ *and* $m_{\tilde{t_1}} < m_{\tilde{\chi}_1^{\pm}+b}$. The limit is shown in Fig. 5.

2.5 The Charged Higgs

CDF reports a search for the charged Higgs boson in the framework of minimal SUSY via its appearance in top decays: $t \rightarrow b+H^+$ followed by $H^+ \rightarrow \tau + \nu_\tau$.[14] This limit rules out a charged Higgs with a mass below 140 GeV for $tan\,\beta > 200$.

2.6 Radiative SUSY Decays

Interest in models where radiative decays of SUSY particles are important [15] was recently piqued by observation of a single event at CDF with the topology of 2 electrons, 2 photons, and large $\not\!\!E_T$. These models in turn predict SUSY signatures in channels such as 2 photons + $\not\!\!E_T$. CDF showed an examination of the 2 photon channel at this conference [16] which found no indication of an excess above background as shown in Fig. 6.

3 Searches for Dijet Resonances

Many new states can have substantial branching fractions into two jets, but this signature is difficult to observe inside the QCD background. The search

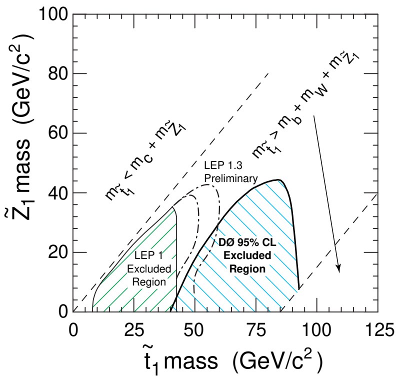


Figure 5: The 95% CL limit in the $m_{\tilde{t}_1} - m_{LSP}$ plane from 1992-93 data from DØ.

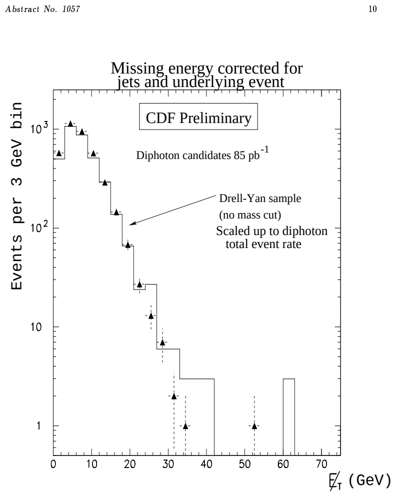


Figure 6: The observed spectrum of diphoton invariant mass, from a CDF investigation of the channel diphoton + $\not{E}_T$.

limits obtained depend on assumptions about the line width of the resonance being searched for.

3.1 Excited Quarks and Other Dijet States in Dijet Events

From the dijet mass spectra obtained by CDF and DØ, cross section upper limits can be obtained for the addition of a resonance of a given width. CDF [17] has reported from the 1992-95 data set a limit curve, shown in Fig. 7(a). DØ reports at this conference [18] a limit in the same channel from 1994-95 data shown in Fig. 7(b).

3.2 Dijet Resonance Produced with a W Boson

Some new particles (Standard Model or SUSY Higgs or technirhos, for example) could be produced in association with W bosons and then decay to two jets. The conventional Higgs cross section is lower than the expected sensitivity in Run I, but the technirho cross section [19] is at least of the same order of magnitude. DØ reports at this conference a cross section times branching fraction limit on such a resonance in the channel W + $b\bar{b}$,[20] as shown in Fig. 8.

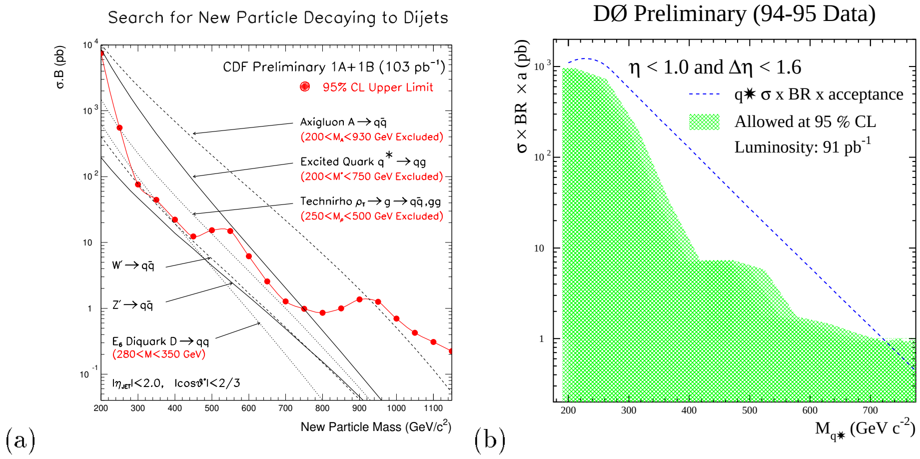


Figure 7: (a) The 95% limit on cross section $\times$ branching ratio into excited quarks, compared to the theoretical excited quark cross section and cross sections for some other new particles, from the CDF dijet analysis. (b) The 95 % limit on cross section $\times$ branching ratio into excited quarks, compared to the theoretical excited quark cross section, from the DØ dijet analysis.

4 Searches for Heavy Gauge Bosons

New gauge bosons are a feature of many sorts of beyond-the-SM physics. Limits quoted here assume Standard Model couplings (and in the case of the limit for right-handed W bosons from DØ, the same CKM matrix for right and left handed states), and can be lower for different assumptions.

4.1 Heavy W Bosons

A conventional search for a heavy W boson looks for extra events in the transverse mass plot above the Standard Model W. Such searches have low background and the limits are determined mostly by integrated luminosity (although they do depend on the coupling assumption, and on the assumption that the accompanying neutrino is massless). CDF and DØ report such limits [21,22] at 650 and 610 GeV respectively.

DØ has reported two other types of search for a heavy W boson.[23] First, there is a search for evidence of a Jacobean peak in the E_T spectrum of high E_T single inclusive electron events. This search would reveal the presence of a heavy W, regardless of the handedness of the new particle, and in the limit of a massless accompanying neutrino gives a mass limit of 720 GeV for the heavy

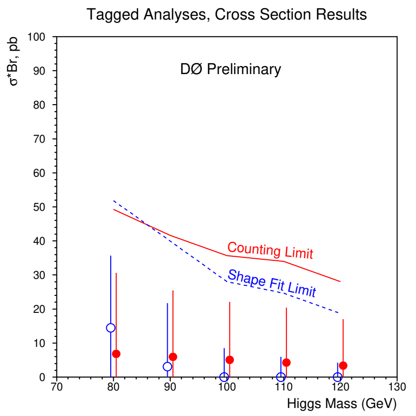


Figure 8: The 95% CL cross section limits on production of a Higgs-like resonance decaying to $b\bar{b}$, produced in association with a W boson.

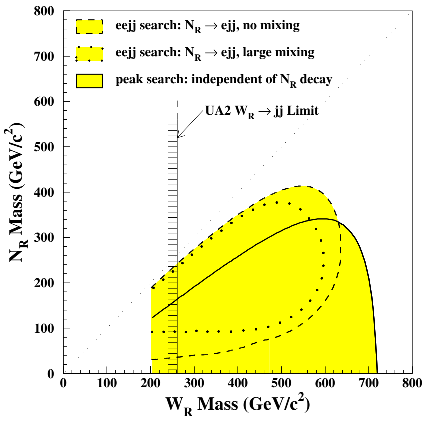


Figure 9: The limit contours from two different searches for a heavy W at DØ. See the text for a description of the searches.

W – significantly higher than from either of the transverse mass searches. This limit is the solid contour shown in Fig. 9. The dashed contour in that figure is obtained from a search for an explicitly right-handed W, decaying to an electron plus a right-handed heavy neutrino which in turn decays to electron plus virtual W, giving as one final state 2 electrons + 2 jets. The lack of such events above predicted SM background is used to set a limit contour that reaches higher neutrino masses than the single electron search. This limit does depend on the right-handed model used, on the CKM matrix assumption, and on the mixing between the standard and the new state.

4.2 Heavy Z Bosons

DØ and CDF have searched for evidence of a heavy Z boson in the dilepton invariant mass spectra. The DØ limit [24] is 670 GeV, using the dielectron channel only and the 1992-95 data set. The CDF limit [21] is 690 GeV, using dielectrons and dimuons and the 1992-1995 data set. Both limits assume standard couplings for the new Z state.

5 Searches for Leptoquarks

Leptoquarks are states of fractional charge which carry both lepton number and color; like heavy bosons, they appear in many variations of non-standard model physics. The constraints from low energy decays [25] imply that, unless the leptoquark is more massive than the current reach at the Tevatron, it must have only flavor-conserving couplings. This makes the predicted decays simple. The leptoquarks decay to leptons and quarks of the same generation only. The quark quantum numbers of the leptoquark mean that it can be strongly pair-produced at the Tevatron, with a cross section independent of the unknown coupling of the leptoquark to quarks and leptons.

5.1 First Generation Leptoquarks

First generation leptoquark pair production will result in three possible final states: 2 electrons + 2 jets; 1 electron, an electron neutrino, and 2 jets; or 2 electron neutrinos + 2 jets. DØ has searched for the first two signatures using 1992-93 data.[26] CDF has a result from its 1989 data for the first signature.[27] The latest result is a preliminary limit from DØ using 1994-95 data, reported in these proceedings.[28] The limit, for the reasonable assumption of equal branching fraction into electron-quark and neutrino-quark decays, is $m_{LQ1} > 143$ GeV for a scalar leptoquark.

5.2 Second Generation Leptoquarks

Pair production of a second generation leptoquark would produce final states analogous to the first generation case, with electron replaced by muon. Both DØ and CDF have results published from the 1992-93 data.[29,30] CDF also has a preliminary limit from 1994-95 data [31] of $m_{LQ2} > 141$ GeV for a scalar leptoquark decaying with equal branching fraction to muon and to muon neutrino.

5.3 Third Generation Leptoquarks

The third generation case has slightly different phenomenology. The quarks involved in the leptoquark decays for the first and second generation leptoquarks would be u,d and c,s respectively. But for the third generation, the decays would be to τ or ν_τ plus t or b quarks. For the mass range below the top quark, a leptoquark of charge state $\pm\frac{2}{3}$ will decay to $\tau + b$ only since $\nu_\tau + t$ is kinematically forbidden. CDF has searched for such a leptoquark,[32] obtaining a limit of 94 GeV for the scalar case and 220 GeV for the vector case.

6 Searches for Fourth Generation Particles

Another kind of new particle accessible at the Tevatron would be quarks and leptons from a possible fourth generation (with massive neutrinos, of course, to conform with LEP data). There are two searches for such particles presented to date, both from DØ.

6.1 b' Quarks

The charge $\frac{1}{3}$ quark of a fourth generation is required by LEP I data to be heavier than $\frac{1}{2}$ the Z^0 mass, but could possibly be lighter than the top quark. Earlier top searches [33] which did not require b-tagging of the final state would limit a b' which decayed semileptonically to charm to a mass greater than 131 GeV. However, if the CKM suppression of the decay to charm is great enough, the b' might decay wholly or in part through flavor-changing neutral current modes, for example $b+\gamma$, $b+gluon$, or $b+Z$. For the mass region between the LEP I limit and $m_Z + m_b \approx 95$ GeV, the decays to Z are forbidden and the branching ratio into $b + \gamma$ has been calculated.[34] DØ has searched for b' pair production with two possible final states: $\gamma + 3$ jets, one of which is tagged as a b jet, and $2\gamma + 2$ jets. Each search separately rules out a b' decaying via FCNC modes with mass between 45 and 95 GeV.[35]

6.2 Heavy Neutrinos

DØ[36] has also used its trielectron channel search in the 1992-93 data to set limits on a heavy neutrino that mixes with the electron neutrino, in terms of the mass and mixing parameter. The exclusion contour extends the LEP I limit to a mass of ≈ 70 GeV, for mixing parameter $(U_{e4})^2 > 0.1$.

7 Searches for New Physics in Distributions

New physics is not necessarily first signalled by the observation of production of a specific new particle type. It may also appear as a deviation in the shape of a distribution or as a difference from the expected value of a particular coupling between particles as calculated within the Standard Model. Several limits on new physics are obtained from analyses of this sort using Tevatron data.

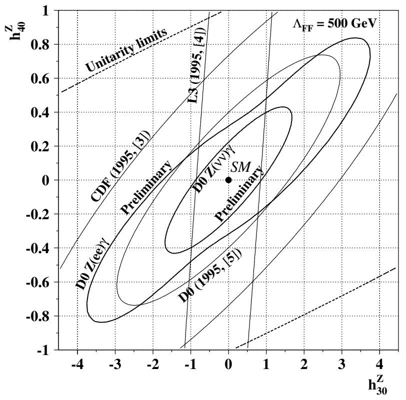


Figure 10: Anomalous coupling limits on ZZγ channel.

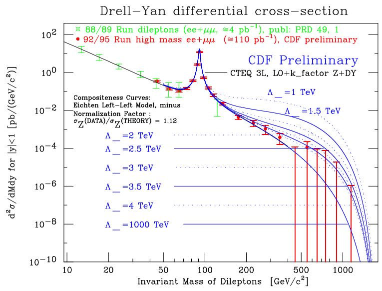


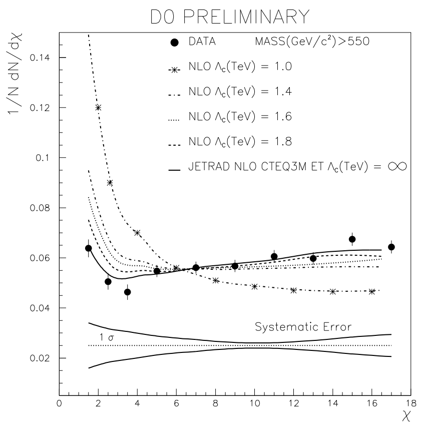
Figure 11: The spectrum of dilepton invariant mass from CDF, with fits to various values of the compositeness scale Λ.

7.1 *Anomalous Triboson Couplings*

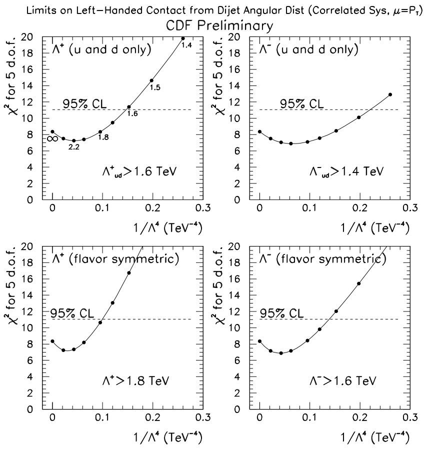
One sector which has been diligently searched at the Tevatron for signs of new phyics is the measurement of triboson couplings (WWZ, $WW\gamma$, $ZZ\gamma$, $Z\gamma\gamma$). The Standard Model predictions for the couplings are well known, and several readily observable final states at the Tevatron can be used (via counting experiments or fits to $E_{T\gamma}$ spectra) to set limits on new physics expressing itself through anomalous couplings appearing in these diagrams. Limits on these couplings have been set by DØ [37,38] and CDF [39] in the WZ, $W\gamma$, and $Z\gamma$ final states, with the W and Z decaying via electron or muon modes. The tightest limit from such a search is a new report from DØ [38] of a measurement in the $Z(\nu\nu)\gamma$ channel, for which the result is shown in Fig. 10.

7.2 *Contact Interactions: Drell-Yan Mass Distributions*

CDF [40] has reported limits on the scale characterizing a possible contact term interaction between quarks and leptons, determined by fits to the observed dilepton invariant mass spectrum. The spectrum and some of the fits are shown in Fig. 11. With the assumption that the contact interaction is between left-handed currents and is the same for electrons and muons, the limits obtained are $\Lambda^-_{LL} > 3.8\ TeV$ and $\Lambda^+_{LL} > 2.9\ TeV$ for the cases of constructive and destructive interference with the SM diagram. Limits for other assumptions can be found in Ref. 40.



(a)



(b)

Figure 12: (a) The χ distribution from DØ, compared to NLO QCD and to expectations for various compositeness scales Λ. (b) The 95 % limits on compositeness scale Λ, from the ratio of two regions in χ, from CDF.

7.3 Contact Interactions: Dijet Angular Distributions

Both DØ [41] and CDF [42] have reported at this conference on examinations of the angular distribution of dijet events, searching for evidence of compositeness in deviations from the NLO predictions of QCD. Both experiments use the variable $\chi = \frac{(1+cos\theta^*)}{(1-cos\theta^*)}$ which is less sensitive to the assumed parton distribution function than either the cos θ distribution or the inclusive jet E_T spectrum. The DØ result is shown in Fig. 12 (a) and the CDF result in Fig. 12 (b).

8 Future Prospects for New Physics at the Tevatron

This paper has presented a long list of results from the search for new physics at the Tevatron. Nevertheless, there is still much to be done in this field. Not all the analyses presented here include the full 1992-96 Tevatron data set, nor have all the proposed signatures for new physics within the Tevatron's reach been investigated.

8.1 *Further results from Run I*

Supersymmetry limits from the Tevatron have covered most of the territory of standard, supergravity-inspired models using the 1992-93 data set. Several standard channels still remain to be reported from 1994-96 data. There is also the task of more fully exploring the model space: relaxing the R-parity constraint, for example, or looking for less obvious channels such as those suggested in Ref. 15. We also need to finish examining the available leptoquark signatures, to apply the dijet searches to different new particle cross sections and widths, and to complete the list of constraints available on new couplings and contact interaction terms.

8.2 *Expected results from Run II*

In Run II at the Tevatron, the two collider experiments are expected to accumulate 2 fb^{-1} of integrated luminosity. In the upgrades to the detectors, CDF will acquire greater η coverage and DØ will add the capability of central track momentum measurement and displaced vertex tagging. Both detectors will thus be able to continue searching for the signatures explored in Run I, with greater sensitivity due to the increased luminosity and acceptance. Table 2 shows the expected reach for various new particles in Run II.[43] In addition, the sensitivity to anomalous couplings in the gauge bosons will increase by a large factor. New searches (for example, for $t\bar{t}$ resonances and technicolor) will become possible.

Table 2: Expected search reach at the Tevatron in Run II

Particle	Expected mass reach at the Tevatron with 2 fb^{-1}
$\tilde{q}$,$\tilde{g}$	$\approx$ 390 GeV
light $\tilde{t}_1$	$\approx$ 150 GeV
$\tilde{\chi}_1^{\pm}$,$\tilde{\chi}_2^0$	$\approx$ 210 GeV
Scalar leptoquarks (1st and 2nd generation)	$\approx$ 240 GeV
Heavy W and Z	$\approx$ 800-900 GeV
Excited quarks	$\approx$ 800 GeV
Technirhos	$\approx$ 750 GeV

9 Conclusion

Although strenuous efforts have been made to uncover chinks in its armor, the Standard Model remains so far unscathed by Run I searches at the Tevatron.

In the search for supersymmetry, the analyses have begun to move into the difficult realm of top-like signatures, as well as pursuing the traditional $\not\!\!E_T$ channels. The cleanest SUSY channel (trileptons) has been investigated with the full data set from both collider detectors and shows no hint of a signal. Some further exploration of the model dependence of the limits has been undertaken, and has shown the necessity for careful specification of all assumptions in interpreting limits.

For other types of new physics, the search has now been extended to all three generations of leptoquarks (although we do not have final numbers from both experiments). New gauge bosons and fourth generation particles have been searched for in novel ways. Dijet resonance searches have now been reported from both CDF and DØ, and also a prototype W-Higgs associated production search at DØ. Constraints on triboson couplings have been significantly improved, and limits on contact interaction terms are now being reported.

A rich program of new physics searches at the Tevatron will remain interesting into the Main Injector era.

Acknowledgments

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