Fermi National Accelerator Laboratory

FERMILAB-Conf-95/393-E
D0

The Search for New Physics with the D0 Detector

Richard Markeloff
For the D0 Collaboration

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

Northern Illinois University
DeKalb, Illinois 60115

December 1995

Presented at the *10th International Workshop on High Energy Physics and Quantum Field Theory*, Zvenigorod, Russia, September 20-26, 1995

Disclaimer

The Search for New Physics with the DØ Detector

Richard Markeloff
Northern Illinois University
DeKalb, IL 60115

Representing the DØ Collaboration

Abstract

The latest results of searches at DØ for physics beyond the Standard Model are presented. These include searches for new weak vector bosons, second generation leptoquarks, a bosonic Higgs, SUSY particles (squarks, gluinos, winos, zinos, and a light stop squark), and a fourth generation heavy neutrino. For each search, backgrounds and physics signals are discussed. No evidence for new physics has been observed. Limits on cross sections and masses are presented.

1 Introduction

The DØ detector is a large, general purpose detector built to study $p\bar{p}$ collisions at the Fermilab Tevatron. A detailed description of the apparatus can be found in Reference [1]. From 1993-1993 the DØ experiment collected approximately 13 pb^{-1} of data at $\sqrt{s} = 1.8$ TeV. We present here the results of several searches through these data for evidence of new particles.

In the discussions that follow, certain details have been omitted for the sake of brevity. Before a detector signal can be identified as having been produced by a specific physics object (such as a photon, electron, muon, or jet) it must satisfy a set of criteria intended to eliminate spurious signals from background sources. For example, consider an energy cluster in an electromagnetic calorimeter. Before we can claim that it came from an energetic electron, we must verify that its spatial profile is consistent with the known shape of an EM shower from an electron and that the tracking system has found a corresponding track. These identification cuts are not described in this report. When we refer to events as containing objects such as electrons, it is implicit that these cuts have been applied. Full details can be found in the References.

2 Searches for Heavy Weak Vector Bosons

Many extensions to the Standard Model predict the existence of additional weak vector bosons, denoted by W' and Z'. We have searched for the W' [2] by looking for events of the type $W' \to e\nu$ and $W' \to \tau\nu$; $\tau \to e\nu\bar{\nu}$ (The DØ detector is unable to distinguish between electrons coming directly from vector boson decays and secondary electrons from τ decays.) We have also performed a similar search for $Z' \to ee$ events [3].

We required W' candidate events to have an electron with large momentum in the plane transverse to the beam ("transverse energy", denoted by E_T) and a large transverse momentum imbalance ("missing transverse energy", denoted by $\not\!\!E_T$). If the total transverse momentum in an event is measured to be substantially different from zero, then the event is assumed to contain one or more energetic neutrinos. The term "transverse energy" comes from the fact that calorimeter data are used to estimate momenta; for very energetic particles, measuring energy is nearly the same as measuring momentum. For this analysis the cuts were $E_T > 20$ GeV and $\not\!\!E_T > 20$ GeV.

Evidence for the existence of a W' was sought by examining the electron-neutrino transverse mass distribution. The transverse mass (m_T) of the electron-neutrino system is defined in the same way as the invariant mass, but includes only vector components in the transverse plane. A signal from W' decays will produce a m_T spectrum different in shape from the spectrum expected from Standard Model processes alone. The primary Standard Model (SM) contributions to the data set come from $W \to e\nu$ events and QCD events with poorly measured energy and a jet that mimics an electron.

We find that the transverse mass distribution for the data sample is consistent with the distribution expected from SM processes alone, as shown in Figure 1. The data can be used to set an upper limit on the ratio of the cross section times branching fraction for $W' \to e\nu$ to the cross section times branching

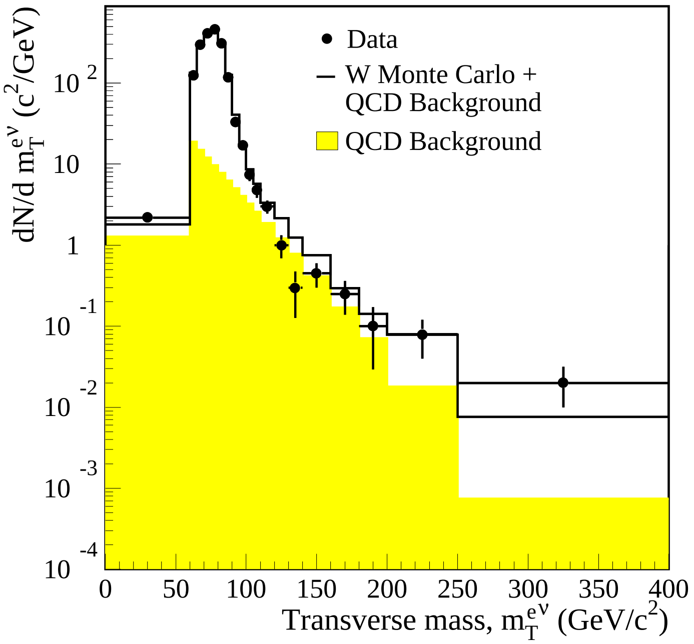

Figure 1: Transverse mass distributions for the W' search. The points represent the data sample; the shaded histogram is the expected distribution from the QCD backgrounds; and the solid line is the sum of the QCD backgrounds and Monte Carlo simulation of $W \to e\nu$.

fraction for the Standard Model $W \to e\nu$, as shown in Figure 2. If we assume that the W' has the same electroweak coupling as the W in the SM, than the data exclude a W' with mass less than 610 GeV at the 95% confidence level.

Events used the Z' search were required to have two electrons with $E_T > 30$ GeV. The Standard Model processes included in this sample are mainly $Z \to ee$, QCD events with fake electrons, and Drell-Yan dielectrons. A Z' will manifest itself as a resonance in the dielectron invariant mass spectrum. Figure 3 shows that the dielectron mass distribution for the data is in good agreement with the spectrum expected from SM processes, with no new resonances visible. As in the W' search, limits can be set on the ratio $\sigma B(Z' \to ee)/\sigma B(Z \to ee)$, as shown in Figure 4. Assuming SM electroweak couplings, a Z' with a mass less than 490 GeV is excluded at the 95% confidence level.

3 The Search for a Right-Handed W Boson

Left-right symmetric extensions of the Standard Model predict the existence of right-handed gauge bosons ($W_R^{\pm}$, Z_R^0) and massive right-handed neutrinos. We have searched for electron decays of a right-handed W, $W_R \to eN$, where N is a heavy right-handed neutrino. The heavy neutrino can then decay via $N \to We$, where the W can be either the W_R or the left-handed SM W, depending upon the mixing angle between the right- and left-handed Ws. For either case, the W can decay into a quark-antiquark pair. This process,

$$W_R \to eN; N \to We; W \to q\bar{q}'$$

yields two electrons and two jets in the final state.

The kinematics of this process vary with the mass of the heavy neutrino, leading to two possible event types. If the neutrino is very massive, then the electron from its decay will be well separated from the jets. If it is light, then the electron will be close to one of the jets and may not be observed. The

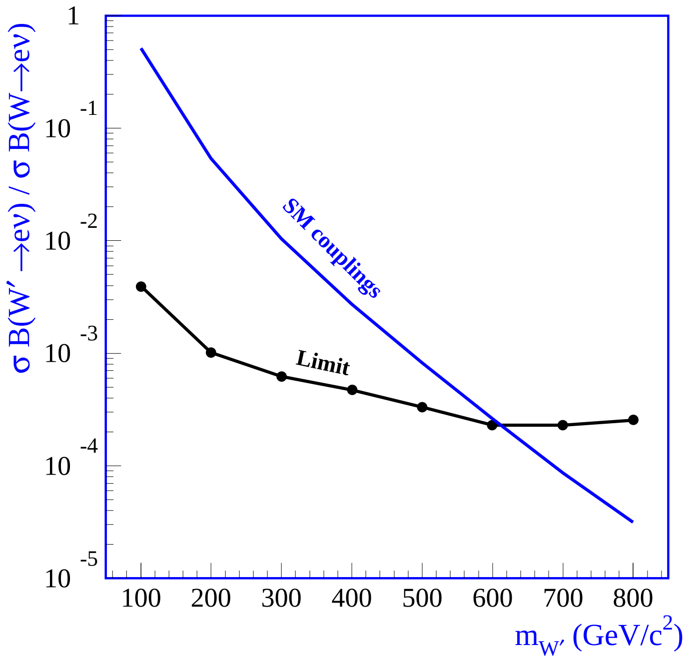

Figure 2: 95% C.L. upper limit as a function of W' mass for $\sigma B(W' \to e\nu)/\sigma B(W \to e\nu)$. The expected value using Standard Model couplings is also shown.

experimental signature for the first case is an event with two high-E_T electrons and two jets; for the second case the signature is a single electron plus jets. Separate W_R searches have been done for these two channels [4].

For the two electron plus two jet case, the cuts applied to the data included requiring $E_T > 25$ GeV for the electrons and jets. The sources of background for this analysis are mainly Drell-Yan dielectrons, QCD jets, and top quark decays. $Z \to ee$ events are rejected by requiring the dielectron invariant mass to be either less than 70 GeV or greater than 110 GeV. One event survives all cuts. The estimated background is 0.5 events, so a signal is not established. However, a conservative upper limit on the W_R cross section can be calculated by assuming that the one event is signal.

For the single electron case, events were selected that had a single electron with $E_T > 50$ GeV. The main backgrounds for this sample are $W \to e\nu$, QCD, and Z decays in which one electron is not identified. A W_R signal would appear as a Jacobian peak in the electron E_T distribution. Figure 5 shows the E_T distribution for the data compared to the distributions expected from W_R decays and SM backgrounds. No W_R signal is evident.

These results can be used to calculate mass limits for the W_R and heavy neutrino. Figure 6 shows the regions of m_{W_R}-m_N space excluded at the 95% confidence level assuming that the W_R has the same electroweak coupling as the SM W_L. The "mixed" and "non mixed" cases refer to the mixing angle between the W_R and W_L. For the "mixed" case maximal mixing is assumed and the neutrino always decays via a W_L. For the "non mixed" case the decay is assumed to always be to a W_R.

4 The Search for Second Generation Leptoquarks

Many theories predict the existence of leptoquarks, bosons that carry both lepton and baryon quantum numbers. If leptoquarks are light (masses less than about 100 TeV) then experimental limits on the branching fractions for rare decays, such as $K^+ \to e^+\nu$, imply that leptoquarks are generational. First

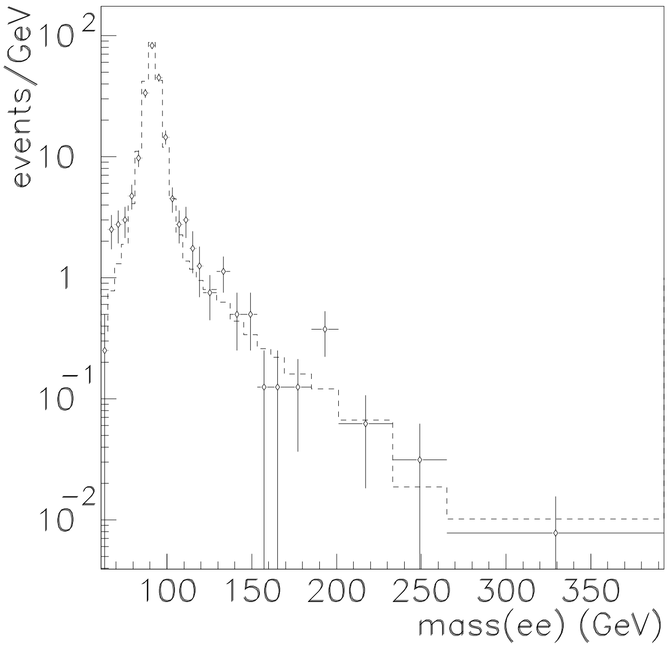

Figure 3: The Z' search dielectron invariant mass distribution (data points). The histogram shows the estimated backgrounds from Standard Model processes.

generation leptoquarks will decay only to e, ν_e leptons and u, d quarks, and so on. A search at DØ for first generation leptoquark pair production has been described elsewhere [5] and here we report the results of a search for second generation leptoquarks [6].

The possible decay modes for second generation leptoquarks are $LQ \to q\mu$ and $LQ \to q\nu_\mu$. Therefore, the decay of a $LQ\bar{LQ}$ pair can produce the following event topologies: $2\mu+2j$, $\mu+ \not{E}_T +2j$, and $\not{E}_T +2j$, where j denotes a jet. Our search focused on the first two event types. The third channel is not useful for setting limits, since the neutrino species cannot be determined.

The main SM backgrounds for the dimuon channel are Drell-Yan dimuons and leptonic decays of $b\bar{b}$ pairs. In Table 1, the number of $2\mu + 2j$ events found for various values of the minimum required muon p_T and jet E_T are compared to the estimated yield from SM processes. The data are consistent with background, with no signal present.

For the search in the single muon channel, we selected events that contained an isolated muon with $p_T > 20$ GeV, two jets with $E_T > 25$ GeV, and $\not{E}_T > 25$ GeV. Expected sources of background are $W \to \mu\nu$ plus jets, $b\bar{b}$, $Z \to \mu\mu$ where one muon is undetected, and $W \to cs \to \mu$ plus jets. To reduce W backgrounds, we made a cut on the muon-neutrino transverse mass. Table 2 summarizes the estimated background and observed number of $\mu+ \not{E}_T +2j$ events for various values of the m_T cut. The data are also consistent with the background estimates.

These results can be used to set limits on the leptoquark pair production cross section as a function of leptoquark mass and β, the branching fraction for $LQ \to q\mu$. Figure 7 shows the regions of m_{LQ}-β space excluded by the these analyses at the 95% confidence level.

5 The Search for a Bosonic Higgs

It is possible that two separate Higgs bosons exist, one responsible for electroweak symmetry breaking and one responsible for flavor symmetry breaking. In such a model [7] the Higgs associated with elec-

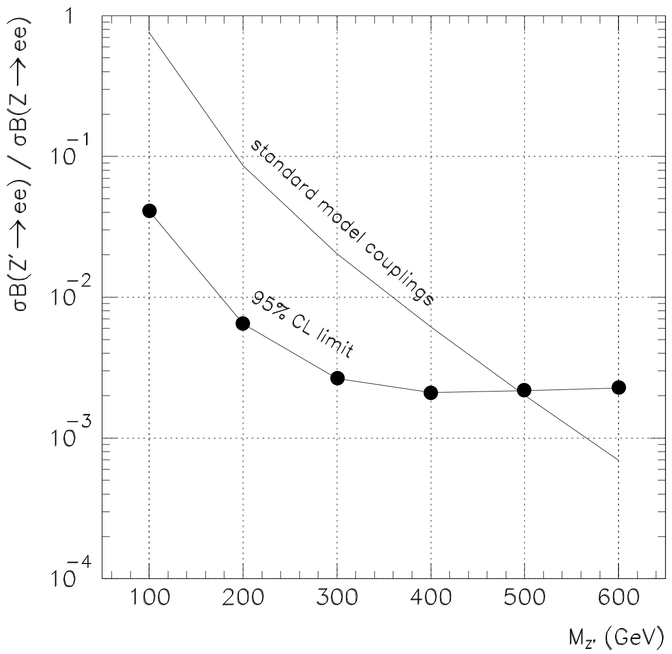

Figure 4: 95% C.L. upper limit as a function of Z' mass for $\sigma B(Z' \rightarrow ee)/sigmaB(Z \rightarrow ee)$. The expected value using Standard Model couplings is also shown.

μ p_T, jet E_T cut	Estimated SM background	Number of events observed
25	1.9 ± 0.7	0
20	3.6 ± 1.0	3
15	11 ± 2.1	12

Table 1: Expected background and number of events observed for the second generation LQ search in the dimuon channel.

troweak symmetry would have Standard Model couplings to vector bosons but suppressed couplings to fermions. We describe here a search for a "bosonic" Higgs whose primary decay mode is $H \rightarrow \gamma\gamma$. This would be expected if the Higgs mass is less than about 90 GeV. For a Higgs mass greater than this, the decay $H \rightarrow WW^*$ (where W^* is an off shell W) would predominate.

The Higgs would be produced in association with a W or Z. The specific signal we have searched for is $(W/Z)H \rightarrow jj\gamma\gamma$ where the jets come from the vector boson decay. The main sources of background are QCD $jj\gamma\gamma$ events and multijet events where jets are misidentified as photons. Events were selected that have photons with $E_T > 20$ GeV and a dijet invariant mass between 65 and 105 GeV. The final data sample contains 4 events; this number is consistent with the background estimates. Figure 8 shows the upper limit on the cross section for $p\bar{p} \rightarrow (W/Z)H \rightarrow jj\gamma\gamma$ as a function of Higgs mass, and compares this to the prediction from Reference [7]. The limit $m_H > 73.5$ GeV is set at the 90% confidence level.

6 Searches for Supersymmetry

We have analyzed the 1992-93 DØ data for evidence of supersymmetric partner particles ("sparticles") of the Standard Model fermions and bosons. These analyses have been done within the framework of the

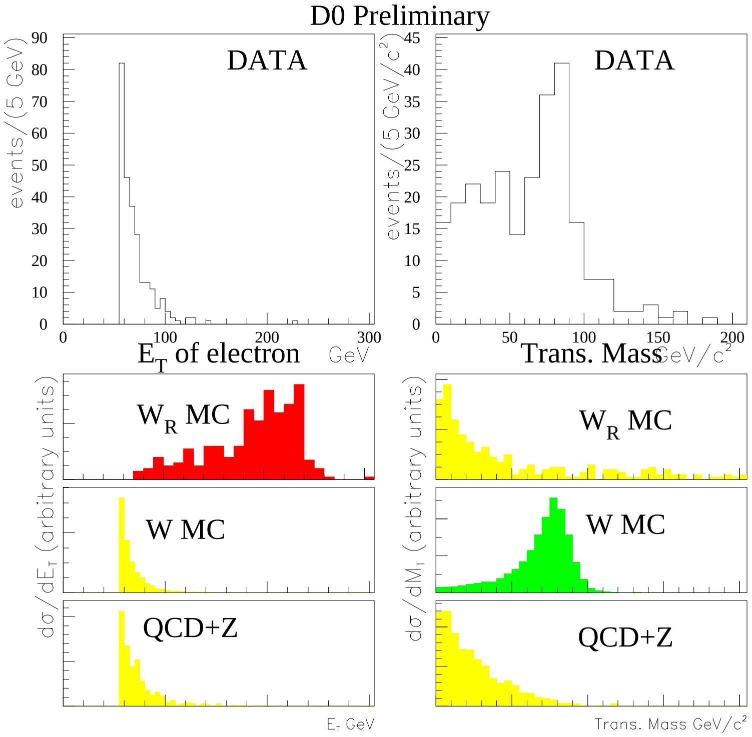

Figure 5: Electron E_T and electron-$\not\!\!E_T$ transverse mass distributions for the single electron W_R search. The E_T distributions show no signal from W_R decays; the m_T distributions indicate that the predominate source of background is $W \rightarrow e\nu$.

Minimal Supersymmetric Standard Model (MSSM) [8]. A quantum number known as R-parity (denoted by R) is associated with particle and sparticle states. Particles have $R = 1$ and sparticles have $R = -1$. We assume that R-parity is conserved, which implies that sparticles must be produced in pairs. It also follows that the lightest supersymmetric particle (LSP) must be stable. We further assume that the LSP is the lightest zino ($\tilde{Z}_1$) and that it escapes detection.

6.1 The Search for Squarks and Gluinos

For this search, we assume that all squarks except the stop are mass degenerate. We have looked for events in which squarks and gluinos cascade decay through lighter winos and zinos (also known as charginos and neutralinos) into final states containing only quarks and the LSP. If the gluino is heavier than a squark, then a possible gluino decay chain is

$$\tilde{g} \rightarrow \bar{q}\tilde{q}; \;\; \tilde{q} \rightarrow q\tilde{Z}_2; \;\; \tilde{Z}_2 \rightarrow q\bar{q}\tilde{Z}_1$$

m_T cut	Estimated SM background	Number of events observed
95	2.4 ± 1.0	0
85	3.7 ± 1.3	3
75	5.6 ± 2.0	5

Table 2: Expected background and number of events observed for the second generation LQ search in the single muon channel.

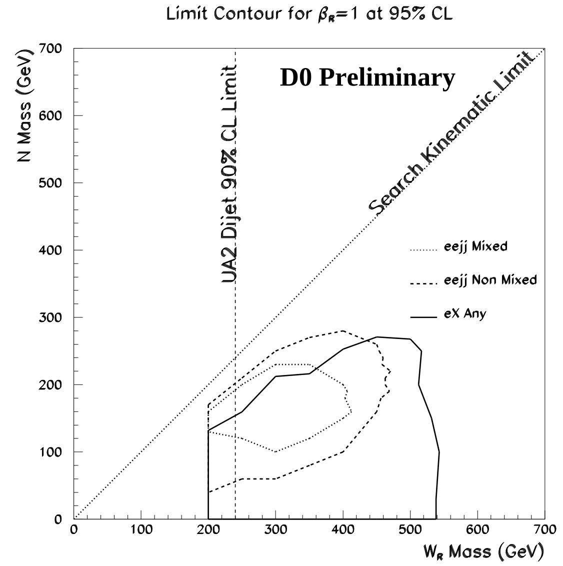

Figure 6: The regions inside the contours are excluded by the W_R searches at the 95% C.L. Standard Model couplings are assumed.

However, if $m_{\tilde{g}} < m_{\tilde{q}}$, then the decay would look like

$$\tilde{g} \to q\bar{q}\tilde{Z}_2;\ \ \tilde{Z}_2 \to q\bar{q}\tilde{W}_1;\ \ \tilde{W}_1 \to q'\bar{q}\tilde{Z}_1$$

The experimental signature in both cases is two or more jets plus $\not\!\!E_T$. Similar cascades producing the same signature exist for squark decays.

We analyzed two separate data sets for this search. The first set contains events with $\not\!\!E_T > 75$ GeV and three jets above an E_T threshold of 25 GeV. The second set consists of events with $\not\!\!E_T > 65$ GeV and four jets with $E_T > 20$ GeV. The dominate background sources for both samples are vector boson decays and QCD events with mismeasured jets. We found the number of events in both samples to be consistent with our estimates of SM backgrounds. Figure 9 shows the $\not\!\!E_T$ spectrum for the 3 jet sample. The data are seen to be reasonably consistent with the estimated background and a SUSY signal, such as the simulated one shown, can be ruled out.

Figure 10 shows the 95% C.L. limit contour in the $m_{\tilde{q}}$-$m_{\tilde{g}}$ plane established by this study. Figure 10 also shows previously published squark-gluino mass limits, including an earlier DØ result [9] based on an analysis of only three jet events.

6.2 The Search for Winos and Zinos

This search looked for the lightest chargino ($\tilde{W}_1$) and next-to-lightest neutralino ($\tilde{Z}_2$). The dominant production mechanism for these sparticles at the Tevatron is expected to be the s-channel reaction through an off-shell W: $p\bar{p} \to W^* \to \tilde{W}_1\tilde{Z}_2$. We then consider the subsequent decays of the $\tilde{W}_1$ and $\tilde{Z}_2$:

$$\tilde{W}_1 \to \tilde{Z}_1 W^*;\ \ W^* \to f\bar{f}'$$

and

$$\tilde{Z}_2 \to \tilde{Z}_1 Z^*;\ \ Z^* \to f\bar{f}$$

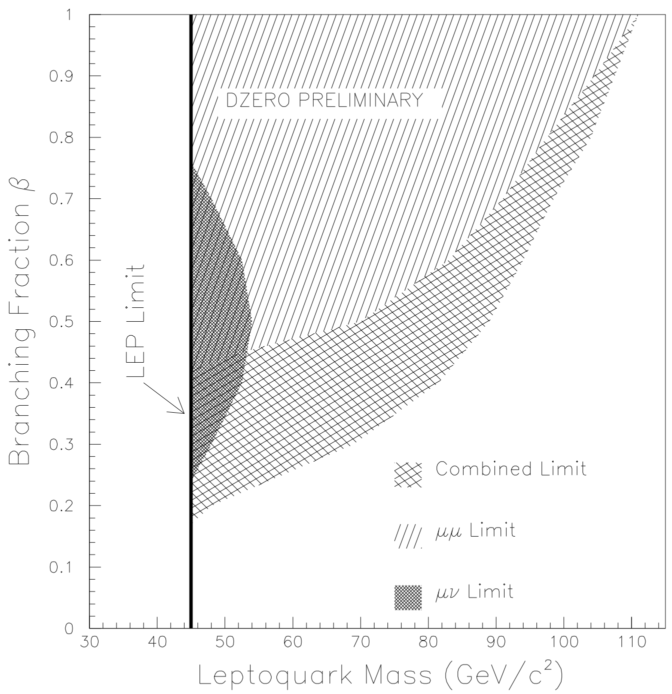

Figure 7: The shaded regions of parameter space are excluded by the DØ second generation leptoquark searches at the 95% C. β is the $LQ \to q\mu$ branching ratio.

where $f\bar{f}$ represents the Standard Model fermions $q\bar{q}$ or $\ell\bar{\nu}$. Alternatively, the zino can decay via

$$\tilde{Z}_2 \to f\tilde{f};\quad \tilde{f} \to \tilde{Z}_1\bar{f}$$

where $\tilde{f}$ represents a squark or slepton. Considering all the possible decays, there are four possible event topologies:

1. $\not\!\!E_T$ + four jets
2. $\not\!\!E_T$ + two jets + one lepton
3. $\not\!\!E_T$ + two jets + two leptons
4. $\not\!\!E_T$ + three leptons

The last event type is the one we have looked for [10]. This signature is relatively uncontaminated by hadronic activity and has few Standard Model backgrounds. We selected events that had three isolated leptons in one of the following combinations: eee, $ee\mu$, $e\mu\mu$, and $\mu\mu\mu$. The leptons were required to have $p_T > 5$ GeV. An additional cut of $\not\!\!E_T > 10$ GeV was imposed on the trielectron events to reduce backgrounds from Drell-Yan and Z events containing a photon or π^0. Muon pairs were required to have an invariant mass greater than 5 GeV in order to eliminate J/ψ decays.

Backgrounds were estimated to be about one event per channel. After all cuts were applied, no trilepton events were found. The 95% C.L. upper limit on the $p\bar{p} \to \tilde{W}_1\tilde{Z}_2$ cross section times branching fraction for $\tilde{W}_1\tilde{Z}_2 \to 3\ell + X$ as a function of the wino mass calculated from this result is shown in Figure 11.

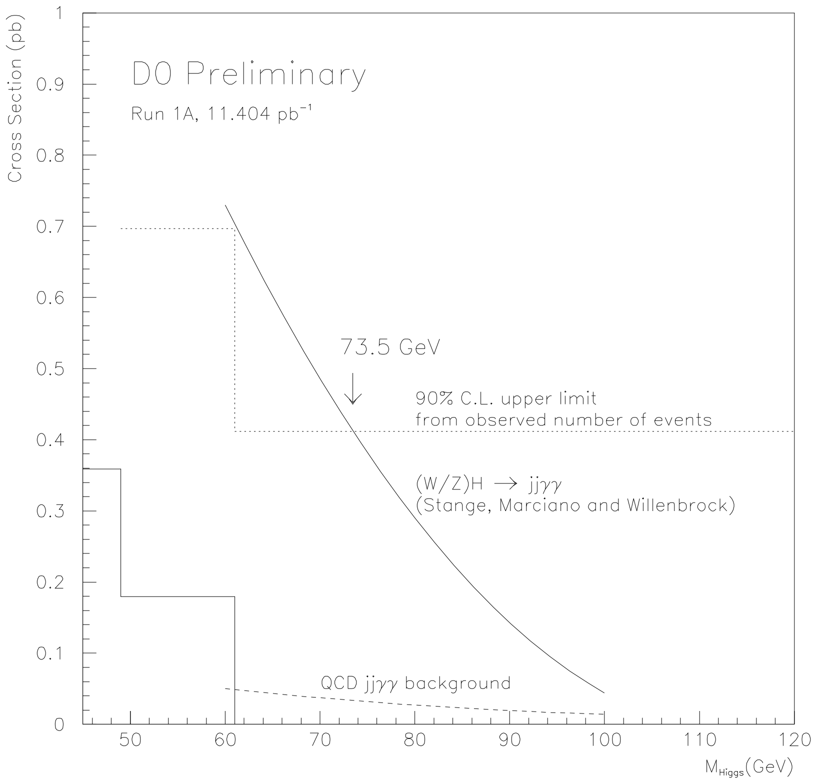

Figure 8: Cross section for $p\bar{p} \to jj\gamma\gamma$ as a function of the $\gamma\gamma$ invariant mass. The solid histogram is from the data and the dotted histogram shows the upper limit for the process $(W/Z)H \to jj\gamma\gamma$.

6.3 The Search for a Light Stop Squark

It is possible that the lightest squark could be the stop ($\tilde{t}$). The $p\bar{p} \to \tilde{t}\bar{\tilde{t}}$ cross section could be large enough for a stop signal to be found in the DØ data. If the stop is heavier than the lightest wino, then the dominant decay is $\tilde{t} \to b\tilde{W}_1$. This gives a signature for $\tilde{t}\bar{\tilde{t}}$ similar to top. However, if the stop is lighter than the $\tilde{W}_1$ and all other squarks and sleptons, then the dominant decay is $\tilde{t} \to c\tilde{Z}_1$. The signature for $\tilde{t}\bar{\tilde{t}}$ will then be two acollinear jets plus $\not\!\!E_T$. It is this signal that we have looked for [11]. The major backgrounds are events with vector bosons plus jets and QCD events with poorly measured jets.

We selected events that had $\not\!\!E_T > 40$ GeV and two jets with $E_T > 30$ GeV. To reduce vector boson backgrounds, events were rejected if they contained an electron or muon with $p_T > 10$ GeV. The final data sample contains 3 events. The estimated SM background is 3 ± 1 events, so no signal was found.

Figure 12 shows the region in stop mass-LSP mass space excluded by this analysis. Since we did not consider three body decays of the stop, the lower boundary of the excluded region is formed by the line $m_{\tilde{t}} = m_b + m_W + m_{\tilde{Z}_1}$.

7 The Search for Fourth Generation Neutral Heavy Leptons

If a fourth generation of quarks and leptons exist, then one would expect that the neutrino (ν_4) would be the lightest member of the generation and the one most likely to be produced at the Tevatron. Studies at SLAC and LEP have shown that if a fourth generation neutrino exists, then it must be heavy ($m_{\nu_4} > 45$ GeV at the 95% C.L.).

We assume that there is mixing between the fourth generation and other generations, so that

$$\nu_i = \sum_{j=1}^{4} U_{ij}\nu_j$$

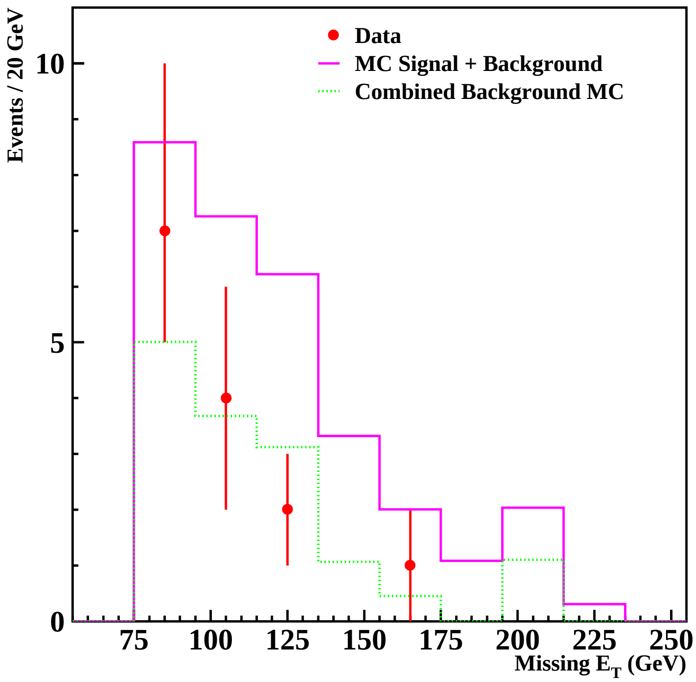

Figure 9: $\not\!\!E_T$ distribution for the 3 jet sample used in the squark and gluino search. The points with error bars represent the data; the dashed histogram is the estimated SM backgrounds and the solid histogram is estimated backgrounds plus a Monte Carlo SUSY signal.

where i = weak eigenstate index, and j = mass eigenstate index. A fourth generation neutrino can then be produced along with an electron in a W decay: $W \to e\nu_4$. If the heavy neutrino then decays via

$$\nu_4 \to eW^*; \quad W^* \to e\nu_e$$

the final state will contain three electrons and $\not\!\!E_T$. This channel was the focus of our fourth generation neutrino search [12].

The data analysis proceeded in the same fashion as the trielectron analysis in the wino/zino search. As in the wino/zino search, the final data set is empty. The exclusion contour in the neutrino mass-mixing parameter plane is shown in Figure 13.

8 Conclusions

We have searched the 1992-93 DØ data set for evidence of new physics, and the Standard Model has emerged unscathed. New limits have been set for a number of exotic particles, as summarized in Table 3. But an additional approximately 70 pb^{-1} of data have been collected in 1994-95 and the analysis of these data is well underway. Results will appear soon from improved and expanded searches for all the exotic particles described in this report. Also in progress are searches for evidence of quark compositeness, wino pair production, and new particles decaying to dijets. There may still be new wonders waiting to be revealed by the DØ detector!

References

[1] S. Abachi *et. al.* Nucl. Inst. and Meth. A338:185-253, 1994.

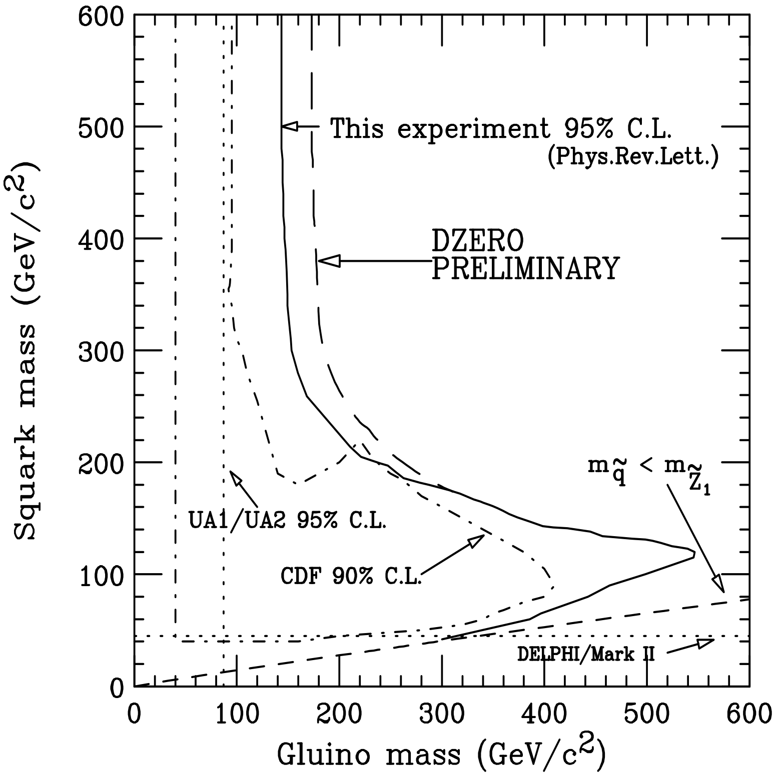

Figure 10: The gluino mass-squark mass combinations inside the contours have been excluded by the various experiments. "D0 Preliminary" is our latest result and "D0 PRL" indicates previously published D0 limits.

[2] S. Abachi *et. al.* Phys. Lett. B358:405-411, 1995.

[3] G. Eppley, *Search for Additional Gauge Bosons.* Ph.D. thesis, Rice University, April, 1995.

[4] S. Abachi *et. al.* Fermilab preprint CONF-95-210-E, 1995.

[5] S. Abachi *et. al.* Phys. Rev. Lett. 72:965-969. 1994.

[6] S. Abachi *et. al.* Phys. Rev. Lett. 75:3618-3623, 1995.

[7] A. Stange, W. Marciano and S. Willenbrock, Fermilab preprint PUB-93/142-T, 1993.

[8] X. Tata, in *The Standard Model and Beyond,* p. 304, ed. J. Kim, World Scientific, Singapore, 1991; H. Nilles, Phys. Rep. 110:1, 1984; P. Nath, R. Arnowitt, and A. Chamseddine, *Applied N=1 Supergravity* (ICTP Series in Theoretical Physics, Vol. 1), World Scientific, Singapore, 1984; H.Haber and G. Kane, Phys. Rep. 117:75, 1985.

[9] S. Abachi *et. al.* Phys. Rev. Lett. 75:618-623, 1995.

[10] S. Abachi *et. al.* Fermilab preprint PUB-95/385-E, 1995.

[11] S. Abachi *et. al.* Fermilab preprint CONF-95-187-E, 1995.

[12] S. Abachi *et. al.* Fermilab preprint CONF-95-254-E, 1995.

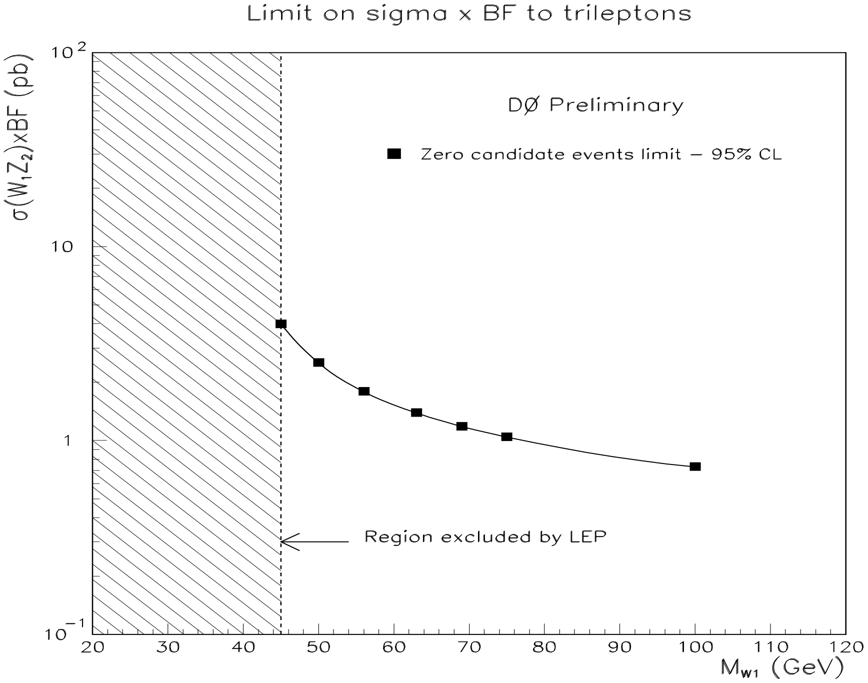

Figure 11: The upper limit on the $\tilde{W}_1\tilde{Z}_2$ cross section times branching fraction for the $\not{E}_T$ plus trilepton channel as a function of wino mass.

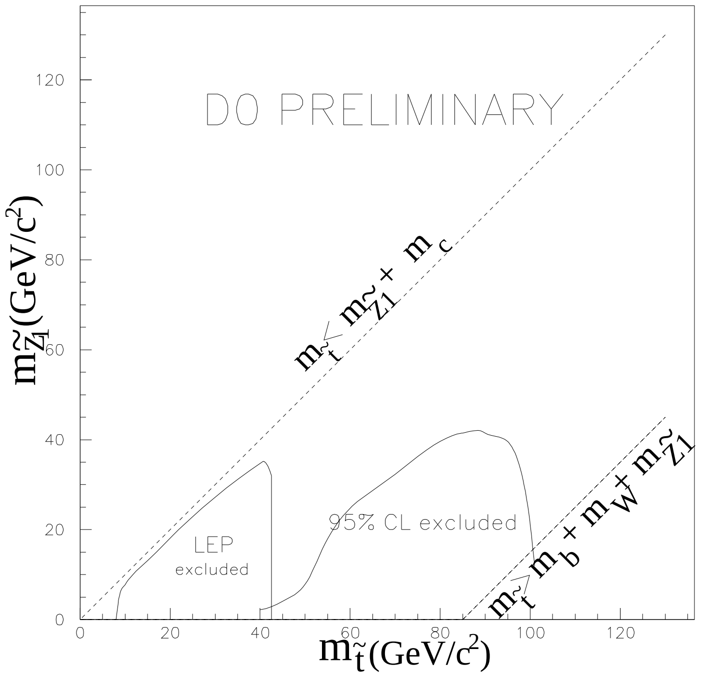

Figure 12: The 95% C.L. exclusion contour for the light stop search.

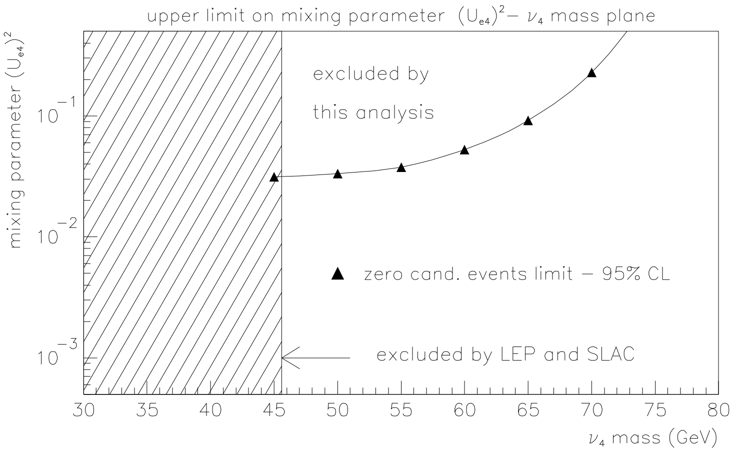

Figure 13: The 95% C.L. exclusion contour in the $|U_{e4}|^2$-m_{ν_4} plane for the fourth generation heavy neutrino search.

New Particle	Channels Searched	Search Results
W'	$W' \to e\nu$	$m_{W'} > 610$ GeV
Z'	$Z' \to ee$	$m_{Z'} > 490$ GeV
W_R	$2e + 2j$, $e + X$	New limit contour
2nd Generation LQ	$2\mu + 2j$, $\mu + 2j + \not{E}_T$	New limit contour
Bosonic Higgs	$2\gamma + 2j$	$m_H > 73.5$ GeV (90% C.L.)
$\tilde{q}$, $\tilde{g}$	$3j + \not{E}_T$, $4j + \not{E}_T$	New limit contour
$\tilde{W}_1$, $\tilde{Z}_2$	$3\ell + \not{E}_T$	New limit contour
Light $\tilde{t}$	$2j + \not{E}_T$	New limit contour
ν_4	$3e + \not{E}_T$	New limit contour

Table 3: Summary of new particle searches desribed in this report. Mass limits are quoted when the particle mass is the only parameter of the model tested; otherwise the limits are a curve in a two-dimensional parameter space. All limits are at the 95% C.L. unless otherwise noted.