D0 NOTE 2890

Search for SUSY in the DØ Experiment

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Introduction

Supersymmetry (SUSY) is a spacetime symmetry which relates bosons to fermions and introduces supersymmetric partners for all the Standard Model (SM) particles[1]. The discovery of such particles would verify that supersymmetry is the correct extension of the standard model and open up vast new areas of work for both experimentalists and theorists. This report will discuss three searches for supersymmetric particles using data taken with the DØ detector in the 1992-1993 Fermilab $\overline{p}p$ collider run at $\sqrt{s} = 1.8$ TeV: search for squarks and gluinos, search for charginos and neutralinos, and search for top squarks.

The DØ Detector

The DØ detector is described in detail elsewhere[2]. It has uranium-liquid argon calorimeters which provide very nearly hermetic coverage for good missing transverse energy ($\not{E}_t$) measurement and good hadronic and electromagnetic resolution for good electron and jet energy measurement. It also has a central tracking system and a muon spectrometer with coverage at large and small angles with respect to the colliding beams.

The Minimal Supersymmetric Model

One of the simplest supersymmetric extensions of the Standard Model (SM) is the minimal supersymmetric standard model (MSSM)[3]. Besides introducing sparticles corresponding to all the SM particles, the MSSM adds two more Higgs doublets and assumes that R-parity, the SUSY multiplicative quantum number is conserved. This means the sparticles are produced in pairs and decay to the stable Lightest Supersymmetric Particle (LSP), which is usually assumed to be the lightest Neutralino ($\tilde{Z}_1$). In

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the MSSM with Super Gravity (SUGRA) inspired mass relations at the GUT scale, the large number of SUSY parameters can be reduced to five[4,6]. These can be chosen at the low energy scale to be $\tan\beta$ (ratio of the Higgs vacuum expectation values), M_{H^+} (mass of the charged Higgs), μ (Higgino mass mixing parameter), and the $\tilde{q}$ (squark) and $\tilde{g}$ (gluino) masses.

Search for Squarks and Gluinos

The experimental signature of squark and gluino cascading decays to the LSP is jets and/or leptons and missing transverse energy ($\not\!\!E_t$), due to the energy carried away by the LSP which does not interact in the detector. In the DØ search, events with leptons were rejected to reduce the background from W and Z leptonic decays. Two independent searches were done: one search required three jets and a high $\not\!\!E_t$ threshold while the other search required four jets and a lower $\not\!\!E_t$ threshold. Results from these two searches have been combined to obtain the final squark and gluino mass limits.

Three jet Analysis

The trigger sample was 9,625 events from an integrated luminosity of 13.5 ± 0.7 pb^{-1}. Offline requirements were:

1) a single interaction
2) $\not\!\!E_t > 75$ GeV
3) three or more jets with $E_t > 25$ GeV, passing quality cuts
4) reject electrons and muons
5) no jet-$\not\!\!E_t$ correlations

Of the 17 events surviving these cuts, one event was rejected because it contained a muon consistent with a cosmic ray, and two other events were rejected because their large $\not\!\!E_t$ was caused by vertex reconstruction errors. The final candidate data sample contained 14 events, consistent with the 14.2 ± 4.4 background events expected from $W + 2,3$ jets and QCD. Results from this analysis have been published [5].

Four jet Analysis

The same trigger sample and integrated luminosity was used. The different offline requirements were:

1) four or more jets with $E_t > 20$ GeV, passing quality cuts
2) $\not\!\!E_t > 65$ GeV

The estimated background was 5.2 ± 2.2 events. The final candidate data sample contained five events, again consistent with the background from the SM.

MSSM Signal Simulation

The MSSM model was used for the signal calculation, assuming SUGRA-inspired degeneracy of squark masses [6]. Only squark and gluino production were considered, no slepton or stop production. The mass of the top quark was set to 140 GeV/c^2, and for the MSSM parameters, the following values were used:

1) Ratio of the Higgs vacuum expectation values $\tan\beta = 2.0$

2) Mass of the charged Higgs $M_{H^+} = 500$ GeV/c^2

3) Higgsino mass mixing parameter $\mu = -250$ GeV

Using the Monte Carlo program ISASUSY, [7] squark and gluino events were generated for pairs of $m(\tilde{q})$-$m(\tilde{g})$ points in the search region and processed through DØ detector simulation, trigger simulation and event reconstruction programs. The signal efficiencies determined from this simulation ranged from 10% -20%.

Calculation of Mass Limits from Cross Sections

Using these signal detection efficiencies, the luminosity and the number of visible events above SM background, a 95% confidence level (C.L.) upper limit cross section was determined. This was compared with a leading order theoretical cross section [7] to determine the lower mass limit for each squark and gluino mass combination. Figure 1 shows the region in the $m(\tilde{g})$-$m(\tilde{q})$ plane excluded by DØ, along with previous results of other experiments [8]. For heavy squarks, a lower gluino mass limit of 173 GeV/c^2 was obtained, and for equal squark and gluino masses, a mass limit of 229 GeV/c^2 was obtained at the 95% C.L.

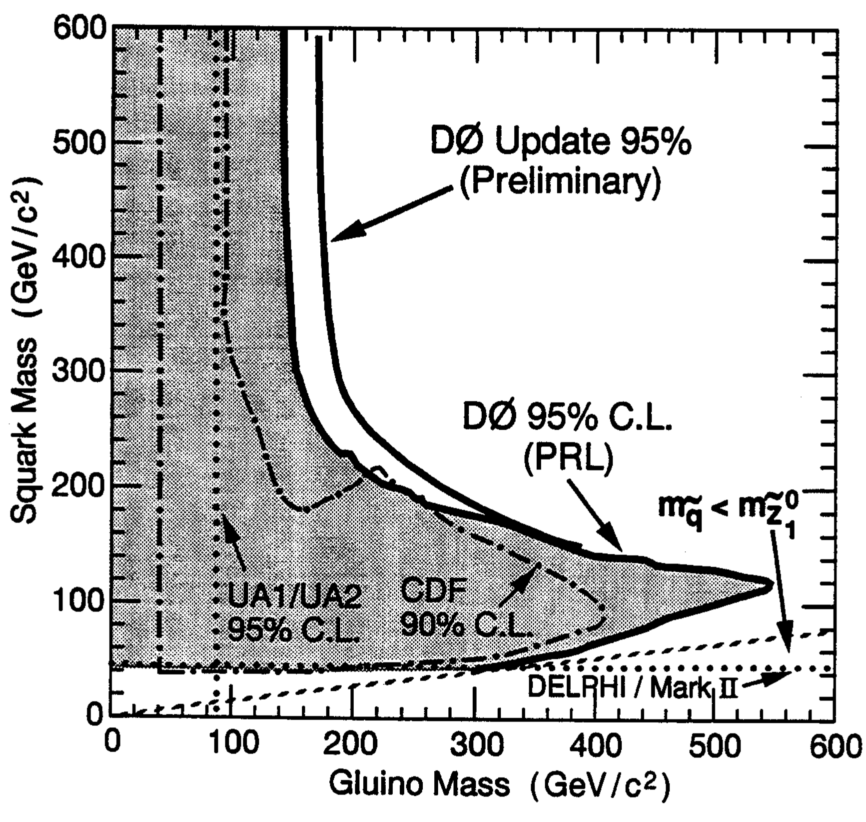

Figure 1: DØ, CDF, LEP and UA1/UA2 squark and gluino mass limits as a function of squark and gluino mass.

Chargino/Neutralinos and The Minimal Supersymmetric Model

In the MSSM and minimal SUGRA model there are two chargino states ($\widetilde{W}_{i,i=1,2}$), and four neutralino states ($\widetilde{Z}_{i,i=1,4}$) corresponding to mixtures of the SUSY partners of the Higgs bosons, W and Z bosons and the photon. As before, the lightest neutralino, $\widetilde{Z}_1$ is assumed to be the LSP. The five SUGRA parameters can be taken as m_0 (the common scalar mass at the GUT scale), $m_{1/2}$ (the common gaugino mass), $\tan\beta$ (ratio of the Higgs vacuum expectation values), A_0 (the common trilinear interaction), and the sign of μ (Higgsino mass mixing parameter). These parameters determine the values of $m_{\widetilde{W}_1}$ and $m_{\widetilde{Z}_2}$.

Chargino/Neutralino Search

Charginos and neutralinos are produced in pairs at $\overline{p}p$ colliders with the $\widetilde{W}_1\ \widetilde{Z}_2$ pair having the largest cross section over much of the SUSY parameter space[9]. The $\widetilde{W}_1$ can decay into $q\overline{q}'$ or $\ell\nu$ plus a LSP, while the $\widetilde{Z}_2$ can decay into $q\overline{q}$, $\nu\overline{\nu}$ or $\ell\overline{\ell}$ plus a LSP. The final state of three leptons + $\not{E}_t$ has the least SM background and is the subject of the DØ search.

Data Analysis

Combinations of single lepton and dilepton triggers were used for the four final states (eee, $ee\mu$, $e\mu\mu$, and $\mu\mu\mu$). Offline, events were required to have $\not{E}_t >$ 10GeV, at least three leptons, but not more than one electron in the forward region (where extra material causes photon conversion into e^+e^-), and mass $(\mu\mu) > 5$ GeV to reduce background from J/ψ events and combinatoric background. No candidates are seen consistent with $\widetilde{W}_1\ \widetilde{Z}_2$ pair production and subsequent decay into trilepton final states. The background consists primarily of single lepton and dilepton events with one or more spurious leptons, except for the $\mu\mu\mu$ channel, where it is mostly from heavy flavor ($b\overline{b}$ and $c\overline{c}$) events. Table 1 gives the integrated luminosity per channel, the number of events passing the offline requirements and the background per channel.

	Channel			
	eee	$ee\mu$	$e\mu\mu$	$\mu\mu\mu$
$\int Ldt(pb^{-1})$	12.5	12.5	12.5	10.8
Require	Number of events passed			
$N_e + N_m \geq 3$	5	2	5	7
$N_e fwd < 2$	4	0	-	-
$\not{E}_t >$ 10 GeV	0	-	-	-
$M_{\mu\mu} > 5$ GeV/c^2	-	-	0	0
Backgrounds	0.8±0.5	0.8±0.4	0.6±0.3	0.1±0.1
DATA	0	0	0	0

Table 1. Analysis cuts for each of the search channels, showing the number of events left after a cut has been applied, and the predicted background per channel.

Cross Section Limits

Detection efficiencies were determined using a combination of data and Monte Carlo simulation. Signal events were generated using ISAJET 7.06 [10] and processed through DØ simulation, programs to determine kinematic and reconstruction efficiencies. Electron identification efficiencies were calculated from monte carlo +data and verified using $Z \rightarrow e^+e^-$ events. Muon identification efficiencies were based on $Z \rightarrow \mu\mu$ and $J/\psi \rightarrow \mu\mu$ event samples. From these efficiencies, the luminosity and zero candidate events a 95% confidence level (C.L.) upper limit on the cross section for producing $\widetilde{W}_1$ $\widetilde{Z}_2$ pairs times the branching ratio into any one of the trilepton final states was determined for $\widetilde{W}_1$ masses from 45 - 100 GeV/c^2. The results from the four channels were combined with the assumption that $B(eee) = B(ee\mu) = B(e\mu\mu) = B(\mu\mu\mu)$. Figure 2 shows the resulting limit in the region above the LEP limit[11] as a function of the mass of the $\widetilde{W}_1$.

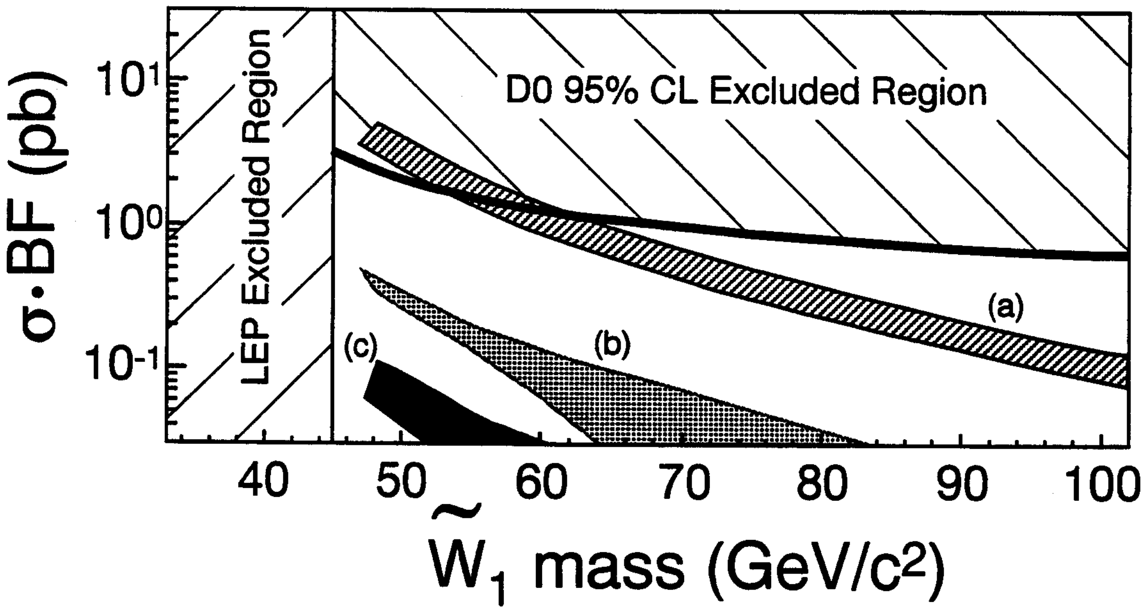

Figure 2: The 95% C.L. limit on cross section times branching ratio into any one trilepton final state, as a function of $M_{\widetilde{W}_1}$, along with the region of $M_{\widetilde{W}_1}$ excluded by LEP. Also shown are bands of theoretical predictions, as described in the text.

For comparison three bands of theoretical curves are shown. Band (a) shows the ISAJET production cross section obtained with a wide range of input parameters, multiplied by a branching ratio of 1/9, which is the maximum branching ratio obtained when the $\widetilde{W}_1$ and $\widetilde{Z}_2$ decay purely leptonically. Bands (b) and (c) show the values obtained from ISAJET with m_o=200-900 GeV/c^2, A_0=0, $m_{1/2}$=50-120 GeV/c^2 and $\mu < 0$. Band (b) is for $\tan\beta = 2$ and band(c) for $\tan\beta = 4$. Upper limits on $\sigma(\widetilde{W}_1\widetilde{Z}_2)$ B($\widetilde{W}_1 \rightarrow \ell\nu\widetilde{Z}_1$) B($\widetilde{Z}_2 \rightarrow> \ell\ell\widetilde{Z}_1$) range from 3.14 pb for $m_{\widetilde{W}_1}$ = 45 GeV/c^2 to 0.63 pb for $m_{\widetilde{W}_1}$=100 GeV/c^2.

The Top Squark and The Minimal Supersymmetric Model

Early MSSM calculations assumed that all squark masses were degenerate. But the high mass of the top quark [12] implies its Yukawa interactions are large, which can drive the top squark mass lower than the other squark masses. Mass splitting by left/right mixing may make one stop state, $\tilde{t}_1$, the lightest squark of all [13].

Search for the Top Squark

Top squarks are produced in pairs in $\overline{p}p$ collisions, with a cross section about 1/10 that of top quark pairs at the same mass, since top quarks are fermions and have extra helicity factors relative to the scalar top squarks. The decay modes of the top squark depend on its mass relative to that of its possible decay products. If $m_{\tilde{t}_1} > m_b + m_{\widetilde{W}_1}$, then the favored decay will be $\tilde{t}_1 \rightarrow b + \widetilde{W}_1$, which is a top-like signature. If the top squark has a mass heavier than the lightest slepton and sneutrino, then it will have three body decays into b + slepton + neutrino or b + lepton + sneutrino. But if the top squark is lighter than the lightest chargino, slepton and sneutrino, then the only decay channel open is $\tilde{t}_1 \rightarrow c + \widetilde{Z}_1$ [14]. This mode has a signature of two acollinear jets and $\not{E}_t$ and was the subject of the DØ search.

Top Squark Analysis

The trigger sample, with a requirement of $\not{E}_t > 35$ GeV, was 83,474 events from a integrated luminosity of 13.5 ± 0.7 pb^{-1}. Offline requirements were:

1) a single interaction

2) $\not{E}_t > 40$ GeV

3) two jets with $E_t > 20$ GeV, passing quality cuts

4) $165° > \phi(jet1, jet2) > 90°$ (acollinear in ϕ)

5) no jet-$\not{E}_t$ correlations

6) reject electrons and muons

Three events survived these cuts. The QCD background from back-to-back jet pairs was eliminated by requiring the jets to be acollinear in ϕ, the opening angle in the plane perpendicular to the beam. The background from lepton W and Z decays was calculated to be 3.49$\pm$ 1.1.7 events. The data is therefore consistent with the SM background.

Mass Limit Calculation

Signal events were generated for various combinations of $m_{\tilde{t}_1}$ and $m_{\widetilde{Z}_1}$ using ISAJET 7.13 [10], and processed through DØ simulation programs to determine efficiencies. From these efficiencies, which ranged from 1% - 5%, and the theoretical production cross section, exclusion limits were obtained at the 95% C.L. Figure 3 shows the region in the $m_{\tilde{t}_1}$ vs $m_{\widetilde{Z}_1}$ plane excluded by DØ along with previous results from the OPAL experiment[15] at LEP.

The allowed region for this decay is bounded by $m_b + m_W + m_{\widetilde{Z}_1} > m_{\tilde{t}_1} > m_c + m_{\widetilde{Z}_1}$. The gap between the LEP excluded region and the DØ excluded region for 60 GeV/c^2 > $m_{(\tilde{t}_1)} > 45$ GeV/c^2 is due to the DØ trigger requirement of $\not{E}_t > 35$ GeV. For the 1994-1995 run, this trigger threshold was reduced to $\not{E}_t > 25$ GeV. When these data are analyzed, the gap should be filled. The highest $m_{\tilde{t}_1}$ value excluded is 93 GeV for $m_{\widetilde{Z}_1}$ = 8 GeV/c^2. For $m_{\widetilde{Z}_1}$ = 44 GeV, masses are excluded for $m_{\tilde{t}_1} > 85$ GeV/c^2.

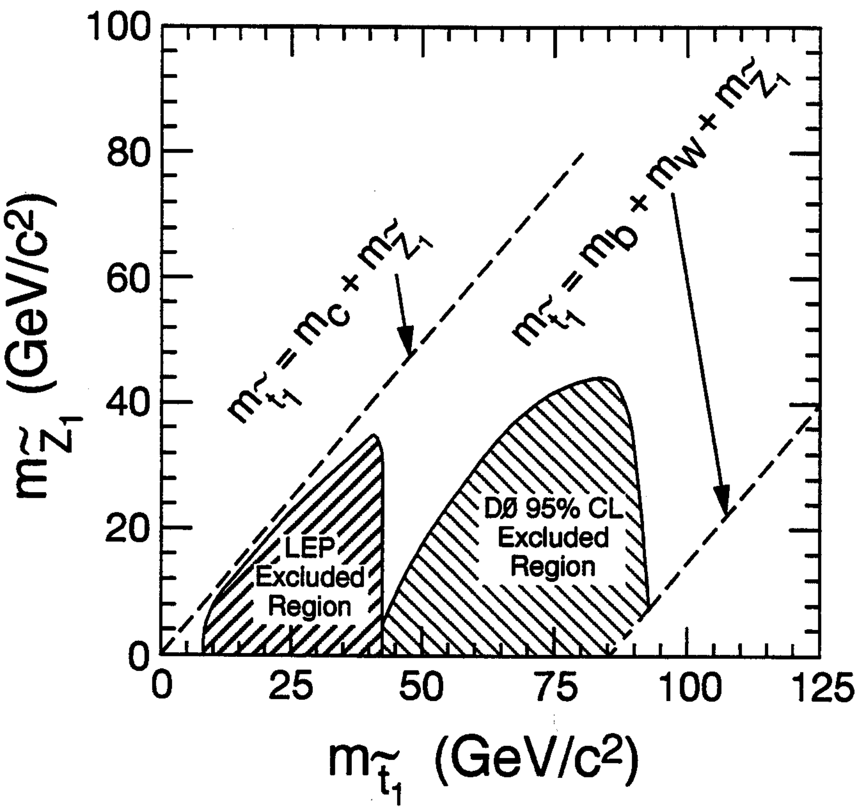

Figure 3: The DØ 95% Confindence Level exclusion contour. Also shown is the result from the OPAL experiment at LEP.

Future Searches

New results from analyzing the 1994-1995 data with an integrated luminosity of over 90 pb^{-1} should be available in the next year. Several studies on selecting the correct vertex in multivertex events have already been done allowing the new analyses to remove the single interaction requirement. Work in progress includes search for squarks and gluinos into leptons, search for charginos/neutralinos into dileptons, and search for R-parity violating SUSY decays. The next year should bring many interesting results and perhaps with ten times as much data some surprises may be in store. The region beyond the Standard Model may be within in our grasp at the Tevatron.

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