SUSY Searches at DØ

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This paper summarizes recent searches for supersymmetric particles using data collected from 1992-1996 by the DØ detector at Fermilab. Limits on the production of bottom squarks, on channels which produce one or two photons plus missing transverse energy, and on R-parity violating decays are reported.

I. INTRODUCTION

Supersymmetry (SUSY) is a hypothetical fundamental space-time symmetry relating bosons and fermions [1]. Supersymmetric extensions to the standard model (SM) feature as yet undiscovered supersymmetric partners for every SM particle. This paper reports the results of recent searches for supersymmetric particles produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. Limits on the production of bottom squarks, on channels which produce one or two photons plus missing transverse energy, and on R-parity violating decays are described.

The data used for these searches were collected by the DØ detector [2] operating at the Fermilab Tevatron Collider during 1992-1996. The DØ detector is composed of three major systems: an inner detector for tracking charged particles, a uranium/liquid argon calorimeter for measuring electromagnetic and hadronic energies, and a muon spectrometer consisting of a magnetized iron toroid and three layers of drift tubes. The detector measures jets with an energy resolution of approximately $\sigma/E = 0.8/\sqrt{E}$ (E in GeV) and muons with a momentum resolution of $\sigma/p = [(\frac{0.18(p-2)}{p})^2 + (0.003p)^2]^{1/2}$ (p in GeV/c). Missing transverse energy ($\not\!\!E_T$) is determined by summing the calorimeter and muon transverse energies, and is measured with a resolution of $\sigma = 1.08$ GeV $+\ 0.019\cdot(\Sigma|E_T|)$.

Most studies of supersymetry introduce a multiplicative quantum number R-parity which is +1 for SM particles and -1 for supersymmetric particles. R-parity conservation implies that the lightest supersymmetric particle (LSP) is stable. If it is also only weakly interacting, it is observed in a detector as missing energy. If R-parity is violated, the LSP can decay to a final state of only SM particles; a search for one such decay is described below.

II. SEARCH FOR BOTTOM SQUARKS

The scalar quarks (squarks) $\tilde{q}_L$ and $\tilde{q}_R$ are the partners of the left-handed and right-handed quarks, respectively. These are weak eigenstates, and can mix to form the mass eigentates, with $\tilde{q}_1 = \tilde{q}_L\cos\theta + \tilde{q}_R\sin\theta$ for the lighter squark, and the orthogonal combination for the heavier squark $\tilde{q}_2$. In most SUSY models, the masses of the squarks are approximately degenerate. But in some models, the lighter top and bottom squarks could have a lower mass than the other squarks due to the mass of the top and bottom quarks. In particular, lighter bottom squarks could arise for large values of tanβ, the ratio of the vacuum expectation values of the two Higgs fields in the minimal supersymmetric standard model. At the Tevatron, squarks are produced in pairs by QCD processes with the production cross section depending on the mass of the squark but not on the mixing angle θ.

DØ has searched for bottom squarks [3] using the decay into the lightest neutralino $\tilde{\chi}_1^0$ via $\tilde{b} \rightarrow \tilde{\chi}_1^0 + b$ and assuming that the $\tilde{\chi}_1^0$ is the LSP and stable. This should be the dominant decay channel provided that the mass of the squark ($m_{\tilde{b}}$) is larger than the combined masses of the b quark and LSP ($m_{\rm LSP}$), and we assumed its branching fraction is 100%. This results in a final state consisting of two b quarks, plus two unobserved stable particles.

Four channels are combined to set limits on the production of bottom squarks. The first required a $\not\!\!E_T$+jets topology, and was previously used to set limits on the mass of the top squark, which was assumed to decay $\tilde{t} \rightarrow \tilde{\chi}_1^0 + c$ [4]. The other three channels also required that at least one jet have an associated muon, which was used to tag b quark decay. These channels were used before to set limits on a charge 1/3 third generation leptoquark with the decay $LQ \rightarrow \nu_\tau + b$ [5]. For all channels, the presence of significant $\not\!\!E_T$ was used to identify the non-interacting LSPs.

Backgrounds arose from events where neutrinos produced significant $\not\!\!E_T$; for example, in W plus multijet events where $W \rightarrow l\nu$.

Events for the $\not\!\!E_T$+jets channel were collected using a trigger which required $\not\!\!E_T > 35$ GeV. During offline analysis, events with two jets ($E_T^{\rm jet} > 30$ GeV), $\not\!\!E_T > 40$ GeV, and no isolated electrons or muons were selected. To eliminate QCD backgrounds, additional cuts were made on the angles between the two jets, and between jets and the missing E_T direction. Data with an integrated luminosity of 7.4 pb^{-1} yielded three events satisfying the selection criteria. Background was estimated to be 3.5 ± 1.2 events, with 3.0 ± 0.9 from W boson decays and 0.5 ± 0.3 from Z boson decays.

The muon channels used either a trigger with two low-p_T muons ($p_T^\mu > 3.0$ GeV/c), a trigger with a single low-p_T muon plus a jet with $E_T > 10$ GeV, or a trigger which required a high-p_T muon ($p_T^\mu > 15$ GeV/c) plus a jet with $E_T > 15$ GeV. Integrated luminosities of 60.1 pb^{-1}, 19.5 pb^{-1}, and 92.4 pb^{-1} respectively were collected using the three muon triggers. The offline analysis used muons in the pseudorapidity range $|\eta_\mu| < 1.0$ with $p_T^\mu > 3.5$ GeV/c. Either two muons, each associated with its own jet, or a single jet-associated muon was required. If the event had only one muon-jet combination, an additional jet with $E_T > 25$ GeV was required. To remove QCD backgrounds, events were selected with $\not\!\!E_T > 35$ GeV and an azimuthal angular separation between the missing energy direction and the nearest jet greater than 0.7 radians. For the single muon channels, backgrounds from W boson decays were removed by cuts on muon-jet correlations; and top backgrounds were minimized by cuts on the scalar sum of jet E_T. Following all selection criteria, two events remained in the data. We estimated there were 1.4 ± 0.5 $t\bar{t}$ events, 1.0 ± 0.4 W boson events, and 0.1 ± 0.1 Z boson events in the sample. The total background for the muon channels was therefore 2.5 ± 0.6 events.

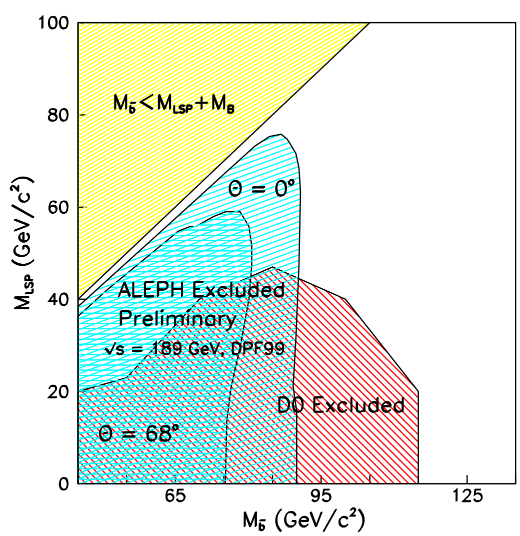

FIG. 1. The DØ 95% C.L. exclusion contour in the $m_{\rm LSP}$ versus $m_{\tilde{b}}$ plane. Also shown are the results from the ALEPH experiment at LEP for minimal ($\theta = 68^o$) and maximal ($\theta = 0^o$) coupling.

Combining the four channels gave five events observed in the data with a total background estimated to be 6.0 ± 1.3 events. We set limits on the cross section by combining the acceptances and integrated luminosities for the different channels. For any given $m_{\tilde{b}}$, we determined the value of $m_{\rm LSP}$ where our 95% C.L. limit intersected the theoretical cross section, and excluded the region where the cross section was greater than our limit. We used the program PROSPINO to calculate the theoretical bottom squark pair production cross section as a function of $m_{\tilde{b}}$ [6]. The excluded region in the $m_{\rm LSP}$ versus $m_{\tilde{b}}$ plane is shown in Fig. 1. We exclude values of $m_{\tilde{b}}$ below 115 GeV/c^2 for $m_{\rm LSP} < 20$ GeV/c^2. For $m_{\tilde{b}} = 85$ GeV/c^2, we exclude the region with $m_{\rm LSP} < 47$ GeV/c^2. Also shown are preliminary limits from the ALEPH experiment at LEP for $\sqrt{s} = 189$ GeV [7]. For most allowable values of $m_{\rm LSP}$, they exclude the region with $m_{\tilde{b}} < 90$ GeV/c^2 for maximal coupling ($\theta = 0^o$).

III. PHOTON PLUS MISSING E_T SEARCHES

Photons can arise in a number of ways during the decays of supersymmetric particles. One is by the decay of the next-to-lightest supersymmetric particle (NLSP) to the LSP, $NLSP \rightarrow LSP + \gamma$. The NLSPs are produced through cascade decays of SUSY particles, for instance $\tilde{q} \rightarrow q + NLSP$.

We utilized diphoton events to set limits on chargino and neutralino masses when the LSP is assumed to be a gravitino [8]. Events were selected which have one photon with $E_T > 20$ GeV and another with $E_T > 12$ GeV. We also required that $\not\!\!E_T > 25$ GeV. Two events remained in 106 pb^{-1} of data. Background was estimated at 2.3 ± 0.9 events mostly from jets misidentified as photons.

We interpret our results in the framework of the minimal supersymmetric model (MSSM). In this framework, the gaugino-Higgsino sector (excluding gluinos) is described by four parameters: M_1 and M_2 are the $U(1)$ and $SU(2)$ gaugino mass parameters, μ is the Higgsino mass parameter, and tanβ is the ratio of the vacuum expectation values of the two Higgs doublets [9]. Our data excludes a region in the (μ, M_2) plane and is insensitive to the choice of tanβ over the range 1.05 <tanβ < 100. For our range of M_1 and M_2 sensitivity, the chargino ($\tilde{\chi}_1^\pm$) and two lightest neutralinos ($\tilde{\chi}_2^0, \tilde{\chi}_1^0$) have masses which are related: $m_{\tilde{\chi}_1^\pm} \approx m_{\tilde{\chi}_2^0} \approx 2 \times m_{\tilde{\chi}_1^0}$. We can therefore express our cross section limit in terms of $m_{\tilde{\chi}_1^\pm}$. If we take tan$\beta = 2$, we exclude $m_{\tilde{\chi}_1^\pm} < 150$ GeV/c^2 and $m_{\tilde{\chi}_1^0} < 77$ GeV/c^2.

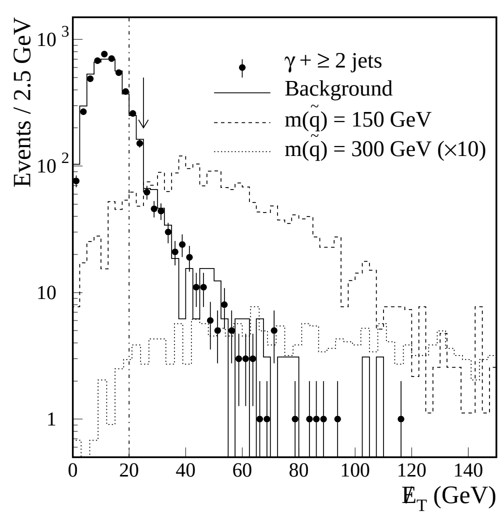

FIG. 2. The $\not\!\!E_T$ distribution of the $\gamma+ \geq 2$ jets sample. The number of background events is normalized to the data for the $\not\!\!E_T$< 20 GeV region. Also shown are the distributions expected from supersymmetry for $m_{\tilde{q}} = m_{\tilde{g}} = 150$ GeV/c^2 and 300 GeV/c^2.

We also searched for SUSY decays to a single photon [10]. We selected events which had a photon with $E_T > 20$ GeV and at least two jets with $E_T > 20$ GeV. We used $\not\!\!E_T$ and H_T, defined as the scalar sum over jet E_T, to separate signal from the background. We required $\not{E}_T > 45$ GeV and $H_T > 220$ GeV. Fig. 2 shows the $\not{E}_T$ distribution before making the H_T cut. Backgrounds came primarily from mismeasurement of $\not{E}_T$ and a real or fake photon, from $W \to e\nu$ events where the electron was misidentified as a photon, and from $W \to l\nu$ where a jet was misidentified as a photon. For an integrated luminosity of 99 pb^{-1}, five events remained in the data compared to an estimated background of 8 ± 6 events.

We interpret our results in terms of squark and gluino production in the context of MSSM models where the NLSP is the second lightest neutralino and the LSP is the lightest neutralino. We vary the MSSM parameters with the constraints that there is a a dominant $\tilde{\chi}_2^0 \to \gamma\tilde{\chi}_1^0$ decay (with branching ratio B), and that $M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0} > 20$ GeV/c^2 [11]. Fig. 3 gives our limits on $\sigma \times B$ as a function of squark mass, which is assumed to be equal to the gluino mass. Also shown is the calculated cross section. For equal squark and gluino masses, a 95% C.L. limit of $m_{\tilde{q}} > 310$ GeV/c^2 is obtained. For unequal masses, the limit becomes 240 GeV/c^2 for squark (gluino) masses when gluinos (squarks) are heavy.

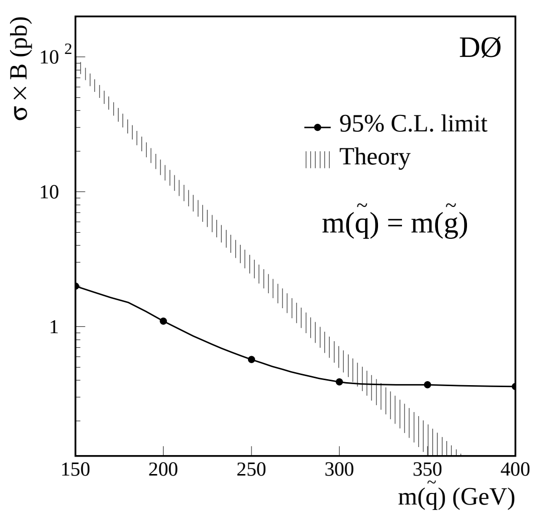

FIG. 3. The 95% C.L. upper limit $\sigma \times B$ as a function of $m_{\tilde{q}/\tilde{g}}$ for the $\gamma+ \geq 2$ jets channel. The squark and gluino masses are assumed to be equal. The hatched band represents the range of expected cross sections for different sets of MSSM parameters.

IV. SEARCH FOR R-PARITY VIOLATING DECAYS

DØ has also searched for SUSY particles with R-parity not conserved. We assume the the amount of non-conservation of R-parity is minimal, and manifests itself solely in the decay of the LSP. Further, we choose the coupling so that the decay $LSP \to e(\nu) + q\bar{q}$ dominates. The event signature is therefore four or more jets from the cascade decays of the initial squark and gluinos plus two electrons from decays of LSPs.

Events for this analysis were required to have two electrons, one with $E_T > 15$ GeV and the second with $E_T > 10$ GeV, and at least four jets with $E_T > 15$ GeV. Electrons were required to be have either $|\eta| < 1.1$ or $1.5 < |\eta| < 2.5$, and to be isolated from other energy deposits. Jets were required to be within $|\eta| < 2.5$. The scalar sum of the E_T of the jets and electrons was required to be greater than 150 GeV. To suppress backgrounds from Z bosons, we rejected events with electron invariant mass within 76–106 GeV/c^2. Two events survived for an integrated luminosity of 96 pb^{-1}. Background was estimated to be 1.8 ± 0.4 events, consistent with the number of events observed in the data. This included 0.4 Drell-Yan events, 0.16 events where either a Z or $t\bar{t}$ produced a dielectron pair, and 1.27 events where a jet was misidentified as an electron.

We interpret our results as an excluded region in the SUGRA parameter space. The SUGRA framework [12] has five free parameters, which are specified at the unification scale - a common mass (m_0) for scalar fermions, a common mass ($m_{1/2}$) for all gauginos, the ratio of the vacuum expectation values of the two Higgs doublets (tanβ), a common trilinear coupling constant (A_0), and the sign of the Higgsino mass parameter (μ). We use ISAJET to generate points in the ($m_0, m_{1/2}$) plane, with tanβ=2, $A_0 = 0$, and $\mu < 0$. The branching ratio of the LSP into a charged lepton or neutrino depends on the SUGRA parameters, and was incorportated into ISAJET using the formula in [13]. The 95% C.L. limits in the ($m_0, m_{1/2}$) plane are shown in Fig. 4. Also overlaid in the figure are the contours for different gluino and squark masses (where we use the average value of the first two generation squark masses). We exclude values of the gluino mass with $m_{\tilde{g}} < 232$ GeV/c^2 and values of the squark mass with $m_{\tilde{q}} < 252$ GeV/c^2.

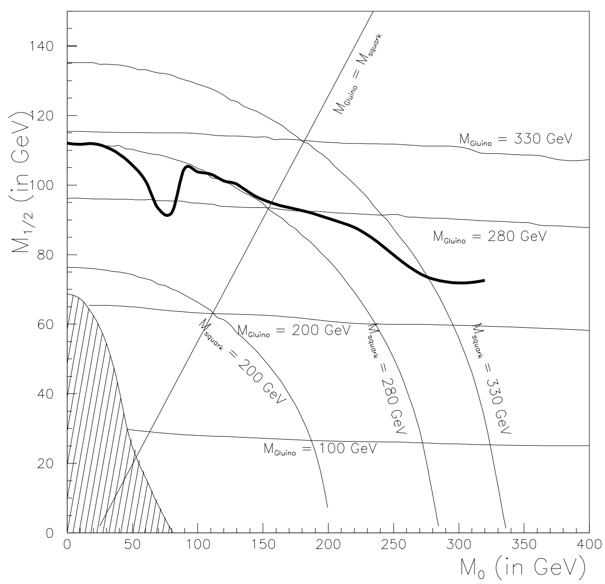

FIG. 4. Exclusion contour in the ($m_0, m_{1/2}$) plane for tanβ=2, $\mu < 0$, $A_0 = 0$ and R-parity violation. The region below the bold line is exclude at 95% C.L. The shaded region is excluded as no electroweak symmetry breaking exists for those choices of mass parameters.

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