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Searches for Supersymmetric Particles in $p\bar{p}$ Collisions with the DØ Detector

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We report on searches for supersymmetric particles with the DØ detector at the Fermilab $p\bar{p}$ collider at $\sqrt{s} = 1800$ GeV. The four searches are: (1) for squarks and gluinos in the jets + $\cancel{E}_T$ channel, (2) for a light top squark in the jets + $\cancel{E}_T$ channel, (3) for squarks and gluinos in the dielectron channel, and (4) for charginos and neutralinos in the trilepton channel. The first two searches use data from the 1992-93 collider run, and the latter two use data from the 1994-95 collider run.

1. INTRODUCTION

In this paper, we discuss four searches made for production of supersymmetric particles, using data from the DØ detector at the Fermilab Tevatron in $p\bar{p}$ collisions at $\sqrt{s} = 1800$ GeV. We have searched for squarks and gluinos using both hadronic and leptonic decay modes, and specifically for a light top squark in the hadronic decay mode. We have also searched for leptonic decays of charginos and neutralinos. All the searches are negative, and we report limits on the production cross sections, and, for specific model assumptions, limits on the masses of supersymmetric particles.

2. THE DØ DETECTOR

The DØ detector is completely described elsewhere [1]. Briefly, its main components are: a central tracking region, occupied by a vertex detector, a central drift chamber, a transition radiation detector, and forward drift chambers; uranium-liquid argon calorimeter modules, contained in three cryostats; and wide- and small-angle muon spectrometers with toroidal magnets and proportional drift tubes. Jets and electrons are identified and their energies are measured by the finely segmented calorimeter, with coverage in $|\eta|$ out to 4.2. Its electromagnetic section is 21 radiation lengths deep, in 4 longitudinal layers,

with an $\eta - \phi$ segmentation of 0.1×0.1 (0.05×0.05 in the third layer, at shower maximum). Muons are identified with negligible punchthrough background, because the calorimeter which shields the muon spectrometer is 7-9 interaction lengths thick and the decay path length is short. Missing transverse energy, $\cancel{E}_T$, is well measured because of the hermeticity of the calorimeter.

3. THE SQUARK/GLUINO HADRONIC MODE SEARCH

Squarks and gluinos can be strongly pair-produced at the Tevatron, with reasonable cross sections. Their decays, in R-parity-conserving models, will cascade through charginos and neutralinos to result in final states containing multijets and significant $\cancel{E}_T$ (from the lightest supersymmetric particle or LSP, which is weakly interacting and stable), and possibly isolated leptons as well. The first signature for which we have searched, using 1992-93 data, is the final state containing multijets + $\cancel{E}_T$. Two separate analyses using somewhat different cuts have been combined to obtain the limit curve shown in Fig. 1. The cuts and their effect on the data are shown in Table 1; note that the data sample is restricted to events consistent with a single interaction occurring in the detector, resulting in an effective integrated luminosity of 7.4 pb^{-1} . In both analyses, the events after final analysis cuts are consistent

Table 1
Analysis cuts for the squark/gluino hadronic mode search

Analysis 1		Analysis 2	
Cut	No. Evt	Cut	No. Evt
Trigger/Preselection	≈ 3500	Trigger/Preselection	≈ 3500
$\cancel{E}_T > 75$ GeV	107	4 jets, $E_T > 20$; $\Delta\phi$ cuts	223
3 jets, $E_T > 25$ GeV;		$\cancel{E}_T > 65$ GeV	5
$\Delta\phi$ cuts	22		
Lepton rejection	17		
Remove cosmic rays, bad vertex	14		
Background predicted	14.6 ± 4.5	Background predicted	6.8 ± 2.4

with predicted background from ordinary vector boson production; various vector boson leptonic decays can give the desired signature if the decay lepton is lost in the detector or misidentified. Also, $Z + 3$ jets events where the Z decays to two neutrinos constitute an irreducible physics background in this search. Ordinary multijet events are not a significant background for the integrated luminosity searched, because of the large $\cancel{E}_T$ cuts used in these analyses.

For the signal samples used to generate the limit curve from these analyses, we used ISAJET(ISASUSY) [2] to simulate a SUGRA-inspired Minimal Supersymmetric Standard Model (MSSM) with $\tan\beta = 2$, $\mu = -400$, and $m_{H^+} = 500$ GeV. In these samples, only the first five flavors of squark (partners of the u, d, s, c, and b) were produced. The top squark can have a quite different mass and decay phenomenology [3], and we searched for its production in a separate analysis, described below.

From these analyses, for this set of MSSM parameters, we conclude that for $m_{\tilde{q}} \gg m_{\tilde{g}}$, $m_{\tilde{q}} > 173$ GeV, and for $m_{\tilde{q}} = m_{\tilde{g}}$, $m_{\tilde{q}} = m_{\tilde{g}} > 229$ GeV.

4. THE TOP SQUARK SEARCH

The large mass of the top quark [4] 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 in fact 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 $\tilde{t}_1 \rightarrow c + LSP$. In this region, $\tilde{t}_1$ pair production and decay will produce the signature two acoplanar jets + $\cancel{E}_T$. DØ searched for this signature using the 1992-93 data, again with the requirement of a single interaction and thus an effective integrated luminosity of 7.4 pb^{-1} . The analysis required $\cancel{E}_T > 40$ GeV,

Figure 1. The 95% CL limit in the $m_{\tilde{q}} - m_{\tilde{g}}$ plane from 1992-93 data.

2 jets with $E_T > 30$ GeV, cuts on the ϕ difference between the $\cancel{E}_T$ and the jets, and no electrons or muons with $E_T > 10$ GeV. The final sample contained 3 candidate events. The background sources are similar to those in the search for larger mass squarks and gluinos described above: vector boson leptonic decays, in which charged leptons are absent or missed. Again, ordinary multijet events are a negligible background with this set of cuts. The total Standard Model background is estimated to be 3.5 ± 1.2 events.

The signal efficiencies were calculated from an ISAJET simulation varying $m_{\tilde{t}_1}$ and m_{LSP} , and a limit curve was computed which is shown in Fig. 2.

Figure 2. The 95% CL limit in the $m_{\tilde{t}_1} - m_{LSP}$ plane from 1992-93 data.

5. THE SQUARK/GLUINO LEPTONIC MODE SEARCH

In our third supersymmetry search, we looked for the signature $ee + 2$ jets + $\cancel{E}_T$, using the full 1994-95 data sample with an integrated luminosity of 92.9 pb^{-1} . The data sample consisted of $\approx 120,000$ events satisfying a trigger which required 1 electromagnetic cluster in the calorimeter with $E_T > 15$ GeV, another calorimeter cluster with $E_T > 10$ GeV, and $\cancel{E}_T > 14$ GeV. The offline analysis required:

- 2 clean electrons, $E_T > 15$ GeV, $|\eta| < 2.5$
- $|m_{ee} - m_{Z^0}| > 12$ GeV, for $\cancel{E}_T < 40$ GeV
- $\cancel{E}_T > 25$ GeV
- 2 clean jets, $E_T > 20$ GeV, $|\eta| < 2.5$

Two candidates passed all the analysis cuts. Note that one of these events is also a $D\bar{O}$ top dilepton candidate; the other event fails the additional cut on the sum of the jet and electron energies placed on top candidates [4]. Top production is the largest single background source for this analysis, with a prediction of 1.2 ± 0.4 events. The sum of all the backgrounds is 3.0 ± 1.3 events, consistent with the 2 events observed.

For this analysis, unlike the previous two, ISAJET 7.13 was used to generate signal samples in the framework of minimal supergravity (SUGRA) [5]. This framework is much more constraining than the MSSM in terms of relations among the SUSY particle masses, since all such relations are fixed by specifying only the five SUGRA parameters m_0 , $m_{\frac{1}{2}}$, A_0 , $\tan \beta$, and $\text{sgn}(\mu)$. We fixed $\tan \beta = 2$, $A_0 = 0$, and $\text{sgn}(\mu) = -1$, and varied m_0 and $m_{\frac{1}{2}}$, and produced signal samples which included pair production of all allowed SUSY particles (but squark/gluino pair production dominates the acceptance over all the relevant parameter space). The limit plot for m_0 vs $m_{\frac{1}{2}}$ is shown in Figure 3(a) for the comparison to squark mass contours and Figure 3(b) for the comparison to gluino mass contours. 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

Figure 3. (a) The 95% CL limit in the $m_0 - m_{\frac{1}{2}}$ plane from 1994-95 data, shown with contours of constant $m_{\tilde{q}}$ calculated with the SUGRA parameters listed in the text. (b) The same limit, shown with contours of constant $m_{\tilde{g}}$.

$\tilde{\nu}$ 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 dielectron modes.

6. THE CHARGINO - NEUTRALINO SEARCH

Two of the lowest mass chargino and neutralino states of the Minimal Supersymmetric Standard Model can be weakly pair produced at the Tevatron: $p\bar{p} \rightarrow W^* \rightarrow \tilde{\chi}_1^\pm + \tilde{\chi}_2^0$. 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 3 leptons plus $\cancel{E}_T$. The branching fraction for these channels depends sensitively on the mass of sleptons in the theory, and other parameters.

We have searched in four channels for this signature: eee , $ee\mu$, $e\mu\mu$, and $\mu\mu\mu$, using the 1994-95 data sample. Triggering requirements, analysis cuts, and the integrated luminosity depended on

the channel. The common requirements for all channels were:

- Lepton $E_T > 5$ GeV
- E_T of triggering lepton(s) $>$ trigger threshold + 2 GeV
- Quality cuts on electrons and muons
- Muon $|\eta| < 1.0$
- $\Delta\phi$ cuts on leading leptons and on leptons and $\cancel{E}_T$

In addition, for the eee channel we required $\cancel{E}_T > 15$ GeV and $|m_{ee} - m_{Z^0}| > 10$ GeV; for the $\mu\mu\mu$ channel we required $\cancel{E}_T > 10$ GeV and $m_{\mu\mu} > 5$ GeV. No events survive the cuts in any of the four channels; the background estimated is 1.35 ± 0.37 events for the sum of the channels. The absence of a signal is interpreted as a limit on cross section times branching fraction to one of the three-lepton final states. This limit is shown in Fig. 4, along with the similarly obtained limit from the 1992-93 data set [6], and the limit from the combination of the two data sets. The theory curves shown in the figure are from ISAJET with various MSSM parameters.

Figure 4. The 95% CL limit on $\sigma \times$ branching fraction to a trilepton channel vs $\tilde{\chi}_1^\pm$ mass, from the 1994-95 data.

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