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# Search for Supersymmetry and Leptoquark States at FNAL

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## Abstract

Searches have been made for first generation scalar and vector leptoquarks by the DØ collaboration and for second generation scalar leptoquarks by the CDF collaboration. The data sample is from the 1992-93  $p\bar{p}$  run at  $\sqrt{s} = 1.8$  TeV at the Fermilab Tevatron Collider. Assuming that leptoquarks are pair produced and decay into charged leptons and quarks with branching fraction  $\beta$ , mass limits at the 95% Confidence Level (CL) have been obtained. For first generation scalar leptoquarks the lower mass limit is 130 GeV/ $c^2$  for  $\beta = 1.0$  and 116 GeV/ $c^2$  for  $\beta = 0.5$ . For first generation vector leptoquarks with  $\kappa$ , the anomalous coupling, of 1.0 and  $\beta = 1.0$ , the lower mass limit is 240 GeV/ $c^2$  and for  $\kappa = 1.0, \beta = 0.5$ , the lower mass limit is 240 GeV/ $c^2$ . For  $\kappa = 0$  and  $\beta = 1.0$ , the lower mass limit is 190 GeV/ $c^2$  and for  $\kappa = 0, \beta = 0.5$ , the lower mass limit is 185 GeV/ $c^2$ . For second generation scalar leptoquarks, the mass limits are 133 GeV/ $c^2$  for  $\beta = 1.0$  and 98 GeV/ $c^2$  for  $\beta = 0.5$ . A search for squarks and gluinos, predicted by Supersymmetric models, was made by DØ in the three or more jets plus  $\cancel{E}_T$  channel. The number of events observed was consistent with background. For heavy squarks, a lower gluino mass limit of 146 GeV/ $c^2$  was obtained, and for equal squark and gluino masses a mass limit of 205 GeV/ $c^2$  was obtained at the 95% CL.

## 1. Introduction

The discovery of new particles not contained in the Standard Model (SM) would help in choosing among the many extensions to the Standard Model have been proposed. This report will discuss searches for two types of new particles: leptoquarks and supersymmetric particles using data from the 1992-1993 Fermilab  $p\bar{p}$  collider run at  $\sqrt{s} = 1.8$  TeV.

## 2. Leptoquarks

Leptoquarks (LQ) are exotic particles which have both lepton and baryon quantum numbers [1]. They appear in extended gauge theories and composite models, and can be scalar or vector particles depending on the model [2]. Leptoquarks link quark and lepton multiplets

of the same generation. They would be easily pair-produced at  $p\bar{p}$  colliders, with a production cross section that depends only slightly on the unknown coupling  $\lambda$  of the leptoquark to ordinary leptons and quarks [3]. Leptoquarks decay into a charged lepton and a quark, with branching fraction  $\beta$ , or into a neutrino and a quark, with branching fraction  $(1 - \beta)$ .

## 3. The DØ Detector

The DØ detector is described in detail elsewhere [4]. It has uranium-liquid argon calorimeters which provide very nearly hermetic coverage for good  $\cancel{E}_T$  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.

#### 4. First Generation Leptoquark Search in $D\bar{O}$

First generation leptoquarks would decay into an electron and a quark or into an electron neutrino and a quark. Two possible experimental signatures for their pair production would be:

- 1) two electrons + two jets
- 2) one electron +  $\cancel{E}_t$  + two jets

The  $D\bar{O}$  sample for the first channel consisted of 14,780 events with two electromagnetic clusters with  $E_t > 15$  GeV, from an integrated luminosity of  $13.4 \pm 1.6 \text{ pb}^{-1}$ .

The offline requirements were:

- 1) two electrons with  $E_t > 25$  GeV passing good electron quality cuts
- 2) two jets with  $E_t > 25$  GeV passing jet quality cuts

All nine events passing these requirements have  $M(ee)$  near the  $Z$  mass. No events remain after making a  $10 \text{ GeV}/c^2$  cut around the  $Z$  mass. The main background for this channel is Drell-Yan production of two electrons, mainly at the  $Z$  resonance, with two jets. The estimated background of Drell-Yan + two jet events with  $M(ee)$  outside this mass region is 0.3 events.

The sample for the second channel consisted of 11,480 events. The offline requirements were:

- 1) one electron with  $E_t > 20$  GeV passing jet quality cuts
- 2) two jets with  $E_t > 20$  GeV passing good electron quality cuts
- 3)  $\cancel{E}_t > 40$  GeV
- 4) transverse mass ( $e, \cancel{E}_t$ )  $> 105 \text{ GeV}/c^2$
- 5) no jet- $\cancel{E}_t$  correlations

No events remained after these cuts. The estimated background from  $W$  + two jet and QCD events was 0.9 events.

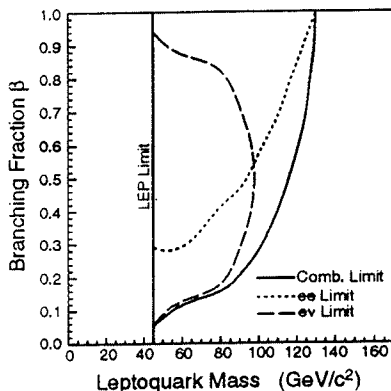


Figure 1.  $D\bar{O}$  95% confidence level lower limit on the first generation scalar leptoquark mass as a function of  $\beta$ .

#### 5. First Generation Scalar Leptoquark Mass Limits

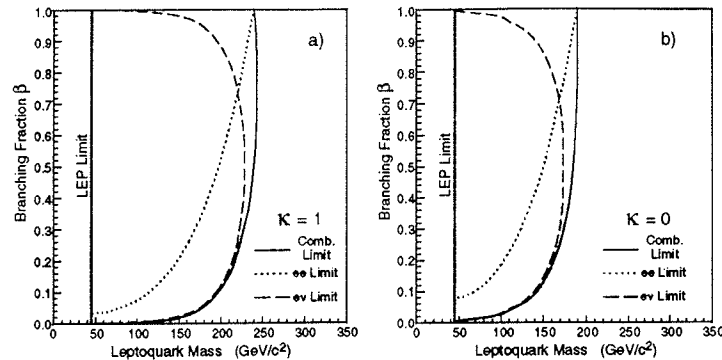
A limit on the leptoquark mass as a function of the branching fraction  $\beta$  can be calculated by comparing the experimental cross section limit with the theoretical prediction. The 95% CL upper limit of the experimental cross section can be obtained from the observation of zero events in each channel, the luminosity, and the  $D\bar{O}$  detection efficiency for these two channels, which is a function of leptoquark mass. For a mass of  $130 \text{ GeV}/c^2$ , the efficiency for the 2 electron channel was 12% and for the 1 electron +  $\cancel{E}_t$  channel it was 9%. The 95% CL upper limit experimental cross section was compared with the theoretically predicted cross section obtained using ISAJET [5] with the MT-LO parton distribution functions [6] to determine the lower mass limit as a function of  $\beta$ . Figure 1 shows the  $D\bar{O}$  95% confidence limit on the mass of the first generation scalar leptoquark. The LQ lower mass limit for  $\beta = 1$  is  $130 \text{ GeV}/c^2$  and for  $\beta = 0.5$  is  $116 \text{ GeV}/c^2$ . These limits differ from those previously published by  $D\bar{O}$  [7] due to a revision of the luminosity calculation.

#### 6. First Generation Vector Leptoquark Mass Limits

Recently, a cross section calculation for the pair production of vector leptoquarks has become available [8]. Since vector leptoquarks are composite particles in some models, their production cross section depends on  $\kappa$ , the anomalous coupling parameter, where  $\kappa = 1$  for gauge coupling and  $\kappa = 0$  for maximum anomalous coupling. Assuming the same detection efficiency for vector leptoquarks as for scalar leptoquarks, and using the calculated vector LQ cross section, one can translate the results of the scalar LQ search into mass limits for vector LQ. The 95% CL mass limits for vector leptoquarks for  $\kappa = 1.0$  (gauge coupling) derived under this assumption are  $M_{LQ} > 240 \text{ GeV}/c^2$  for  $\beta = 1.0$ ;  $M_{LQ} > 240 \text{ GeV}/c^2$  for  $\beta = 0.5$  (see Figure 2a). The 95% CL mass limits for vector leptoquarks for  $\kappa = 0$  (maximum anomalous coupling) are  $M_{LQ} > 190 \text{ GeV}/c^2$  for  $\beta = 1.0$ ;  $M_{LQ} > 185 \text{ GeV}/c^2$  for  $\beta = 0.5$  (see Figure 2b).

#### 7. The CDF Detector

The CDF detector is described elsewhere [9]. The momenta of charged particles are measured in the central tracking chamber, which is surrounded by a 1.4 T superconducting solenoidal magnet. This is surrounded by electromagnetic and hadronic calorimeters, which are used to identify jets. Outside the calorimeters, drift



**Figure 2.** DØ 95% confidence level lower limit on the first generation vector leptoquark mass as a function of  $\beta$ , for (a)  $\kappa = 1$  and (b)  $\kappa = 0$  (see text). These limits assume the same detection efficiency for the decay products of scalar and vector leptoquarks.

chambers in the region  $|\eta| < 1.0$  provide muon identification.

## 8. Search for Second Generation Leptoquarks in CDF

A second generation leptoquark ( $S_2$ ) would decay into a muon and a quark with branching fraction  $\beta$ , or into an muon neutrino and a quark, with branching fraction  $(1 - \beta)$ . CDF has made a search for  $S_2\bar{S}_2$  pairs in the decay channel where both leptoquarks decay into muon+quark. The experimental signature is 2 muons + 2 jets. The CDF trigger sample, based on  $19.3 \pm 0.7 \text{ pb}^{-1}$  of data from the 1992-93 Tevatron run, was 7,958 events. The offline requirements were:

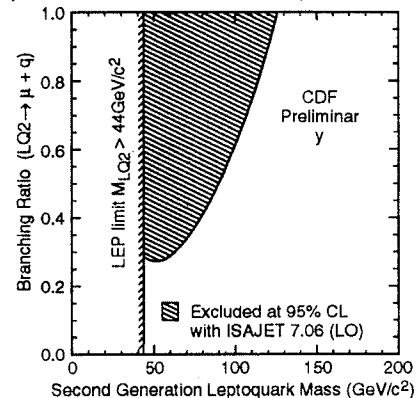
- 1) two good, isolated central muons with  $p_t > 20 \text{ GeV}/c$
- 2) two jets with  $E_t > 20 \text{ GeV}$

After these cuts, 7 events remained. To remove background from  $Z$  production, events with  $75 < M(\mu\mu) < 105 \text{ GeV}/c^2$  were rejected. Two events remained after this cut, with dimuon invariant masses of  $18.9 \text{ GeV}/c^2$  and  $57.9 \text{ GeV}/c^2$ . Background processes include Drell-Yan production of two muons with two jets,  $t\bar{t}$  production in the dimuon channel,  $Z \rightarrow \tau\bar{\tau}$ , and fake muons. The total expected background is  $1.35 \pm 0.50$  events.

## 9. Second Generation Scalar Leptoquark Mass Limits

Two candidate events are observed, consistent with the total background of  $1.35 \pm 0.50$  events. The signal detection efficiencies were determined using the ISAJET Monte Carlo program [5] with CTEQ2L structure functions [10] followed by a CDF detector simulation. The total efficiency ranges from 1.2% for  $40 \text{ GeV}/c^2$  leptoquarks to 16.8% for  $100 \text{ GeV}/c^2$ , and is 12.5% for  $120 \text{ GeV}/c^2$ . Using these efficiencies and the observed

number of events, 95% CL limits on the cross-section times branching ratio were obtained. By comparing these with the theoretical prediction for the cross-section which is based on ISAJET with CTEQ2L structure functions, lower limits on the leptoquark mass as a function of  $\beta$  were obtained. These are shown in Figure 3. The 95% CL lower limit on the mass of a second generation scalar leptoquark for  $\beta = 1.0$  is  $133 \text{ GeV}/c^2$ , and the lower limit for  $\beta = 0.5$  is  $98 \text{ GeV}/c^2$ .



**Figure 3.** CDF 95% confidence level lower limit on the second generation scalar leptoquark mass as a function of  $\beta$ .

## 10. Minimal Supersymmetric Standard Model

One of the simplest supersymmetric extensions of the standard model (SM) is the Minimal Supersymmetric Standard Model (MSSM) [11]. Supersymmetry is a spacetime symmetry which relates bosons to fermions and introduces supersymmetric partners (sparticles) for all the SM particles.  $R$ -parity, the SUSY multiplicative quantum number, is defined as  $R = +1$  for standard model particles and  $R = -1$  for sparticles. We assume that  $R$ -parity is conserved, which implies that sparticles are produced in pairs and decay to the stable Lightest Supersymmetric Particle (LSP), which is usually assumed to be the lightest Neutralino ( $\tilde{Z}_1$ ).

## 11. Search for Squarks and Gluinos

The experimental signature for squarks and gluinos is jets and/or leptons and  $\cancel{E}_t$ , since the LSP does not interact in the detector. In the  $D\bar{O}$  search, 3 or more jets were required. Events with leptons were rejected to reduce the background from  $W$  and  $Z$  leptonic decays. The sample was 9,625 events from an integrated luminosity of  $13.4 \pm 1.6 \text{ pb}^{-1}$ . Offline requirements were:

- 1) a single interaction
- 2)  $\cancel{E}_t > 75 \text{ GeV}$
- 3) three or more jets with  $E_t > 25 \text{ GeV}$  passing jet quality cuts
- 4) reject electrons and muons
- 5) no jet- $\cancel{E}_t$  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  $\cancel{E}_t$  was caused by vertex reconstruction errors. The final candidate data sample contained 14 events, consistent with the  $18.5 \pm 1.9^{+7.6}_{-7.1}$  background events expected from  $W + 2, 3$  jets and QCD.

## 12. MSSM Signal Simulation

The MSSM model was used for the signal calculation, assuming SUGRA-inspired degeneracy of squark masses [12]. Only squark and gluino production were considered, no slepton or stop production. The mass of the top quark was set to  $140 \text{ GeV}/c^2$ . To further specify the parameters, the following values of MSSM parameters were used:

- 1)  $\tan \beta = 2.0$  (ratio of the Higgs vacuum expectation values)
- 2)  $M(H^+) = 500 \text{ GeV}/c^2$  (mass of the charged Higgs)
- 3)  $\mu = -250 \text{ GeV}$  (Higgsino mass mixing parameter)

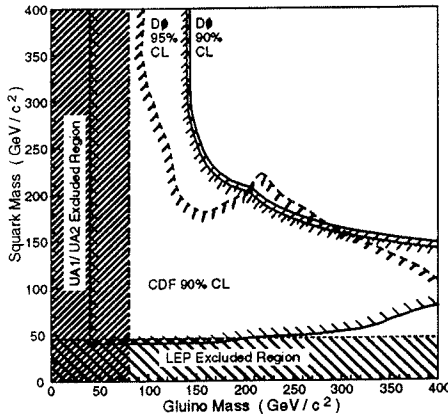


Figure 4.  $D\bar{O}$ , CDF, LEP and UA1/UA2 squark and gluino mass limits as a function of squark and gluino mass.

Squark and gluino events were simulated using the ISASUSY event generator [13] and processed

through the  $D\bar{O}$  triggering, detector simulation, and reconstruction programs. The detection efficiency,  $\epsilon$ , was determined for 28 squark and gluino mass combinations using masses between 100 and 400  $\text{GeV}/c^2$ . As an example, for 200  $\text{GeV}/c^2$  equal mass squarks and gluinos,  $\epsilon = 18.6\%$ . For  $m_{\tilde{g}} = 150 \text{ GeV}/c^2$  and  $m_{\tilde{q}} = 400$ ,  $\epsilon = 6.3\%$ . And for  $m_{\tilde{g}} = 400 \text{ GeV}/c^2$  and  $m_{\tilde{q}} = 150$ ,  $\epsilon = 8.3\%$ . A combination of linear fitting and linear interpolation was used to find efficiencies between grid points.

## 13. Calculation of Mass Limits from Cross Sections

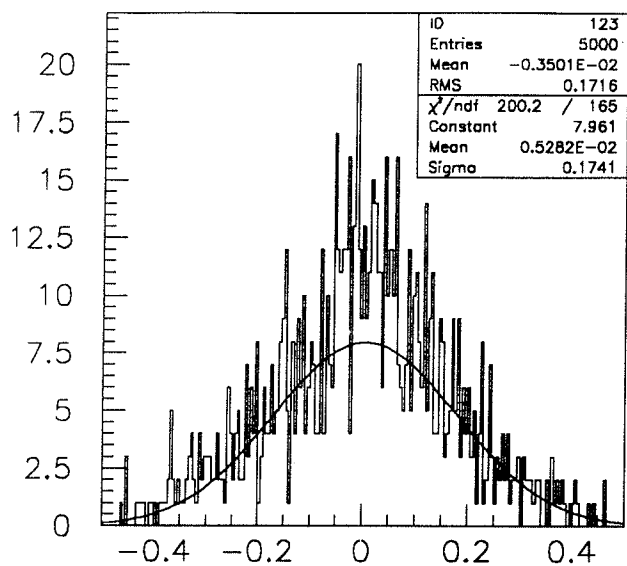
Using these signal detection efficiencies, the luminosity and the number of visible events above SM background, a 95% CL upper limit cross section was determined. This was compared with a leading order theoretical cross section [13] to determine the lower mass limit for each squark and gluino mass combination. For heavy squarks, a lower gluino mass limit of  $146 \text{ GeV}/c^2$  was obtained, and for equal squark and gluino masses, a mass limit of  $205 \text{ GeV}/c^2$  was obtained at the 95% CL.

## 14. Acknowledgements

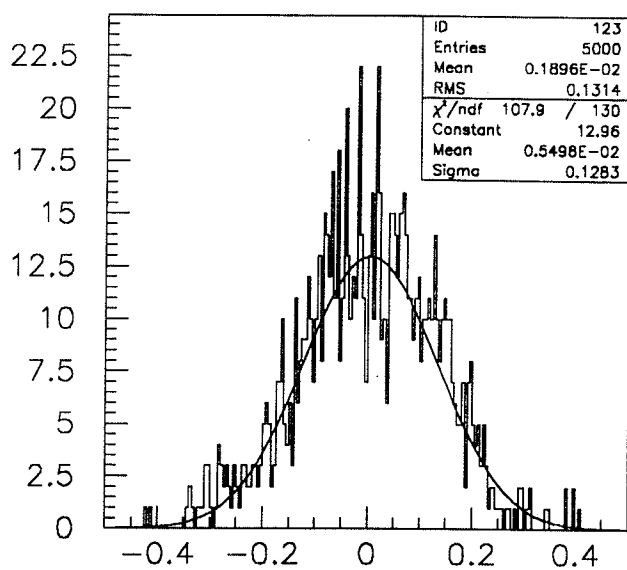
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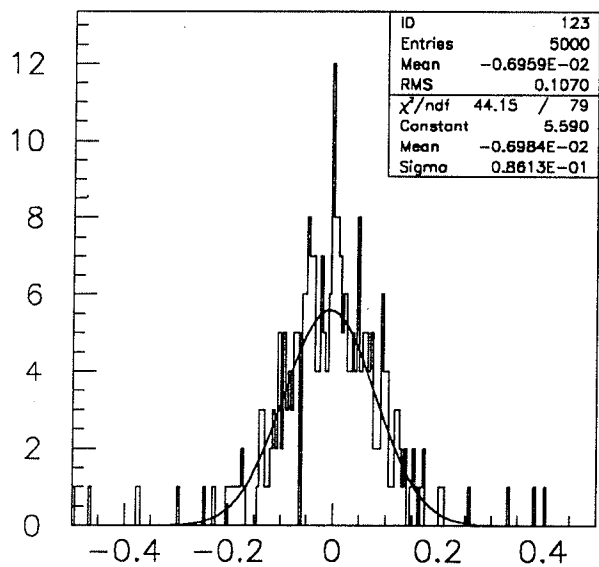
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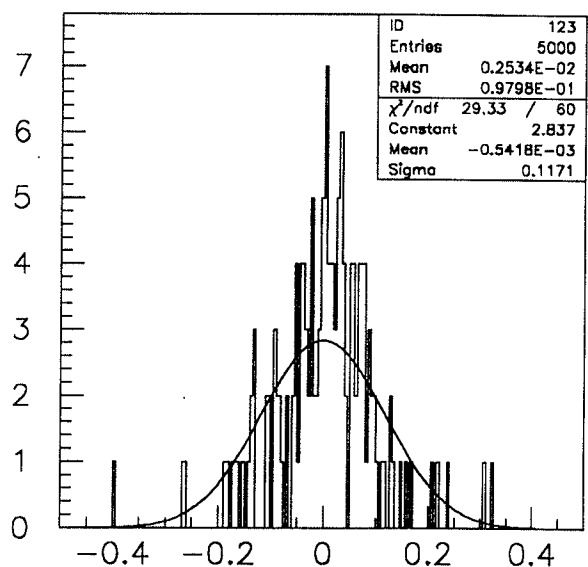
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