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SUSY Searches at DØ

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ABSTRACT

Searches for evidence of supersymmetric particles, and other phenomena beyond the Standard Model, are well underway with the DØ detector at the Tevatron. The DØ detector has good central tracking, excellent energy and missing E_T resolution, hermetic calorimetry, and wide muon coverage. Preliminary results from searches for gluino/squark production and first generation leptoquark production are presented, based on a small fraction of the data taken to date.

1. Introduction

1.1. Overview of Analyses

DØ is a multipurpose collider detector currently in its first data taking run at the Tevatron $p\bar{p}$ collider at Fermilab. The DØ detector design stresses the accurate reconstruction of photons, electrons, jets, and muons.

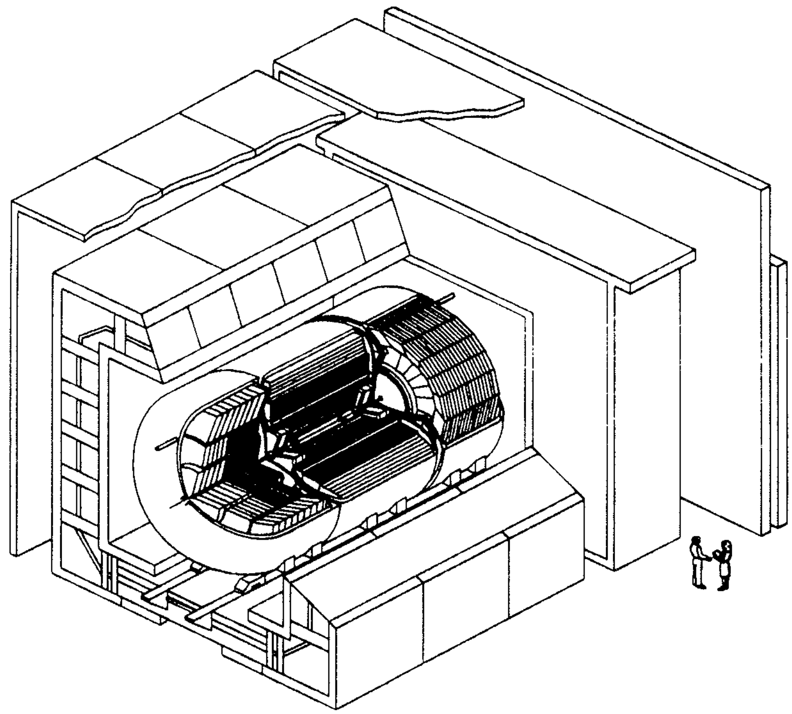
Analyses of the initial collider data are underway. The DØ New Phenomena group has begun searches for the following event signatures of physics beyond the Standard Model :

- Gluino/squark searches based on events with large missing transverse energy ($\not\!\!E_T$);
- Topological gluino/squark searches, including events with m jets + n leptons + $\not\!\!E_T$;
- Searches for production of the lightest chargino and second lightest neutralino ($\tilde{W}_1/\tilde{Z}_2$) via trileptonic final states;
- Leptoquark searches in both the $ee + jets$ and $e\nu_e + jets$ channels;
- Searches for quark compositeness via events with large scalar E_T ;

and other searches (light $\tilde{t}$, massive stable particles, etc.). In order to provide an indication of the physics potential of the DØ detector, two of the more mature analyses will be presented - the $\not\!\!E_T$ gluino search and the leptoquark search.

1.2. The DØ Detector

The DØ detector is described in detail elsewhere[1]. The detector was designed with the goals of providing excellent electron and muon identification and measurement, good calorimetric measurement of high p_T jets, and well controlled measurements of missing transverse energy ($\not{E}_T$). The main components of the DØ detector are multielement central tracking including dE/dx and transition radiation information, but with no central magnetic field; a hermetic fine-grained liquid argon and uranium (LAr/U) calorimeter; and wide muon detector coverage with toroidal magnets for momentum measurements. A cut-away view of the detector is shown in figure 1.



DØ Detector

Figure 1: A cut-away view of the DØ detector, showing the central tracking detectors, calorimeter, and muon detection system.

The central tracking detectors include a vertex chamber consisting of three cylindrical layers of jet cells; a transition radiation detector, with three cylindrical layers of polypropylene foils surrounded by radial X-ray detectors; and a central drift chamber, consisting of four cylindrical layers of jet cells. Forward drift chambers extend tracking coverage down to $\theta \approx 5°$. The spatial resolution of the vertex chamber is typically $50\mu m$ in $R-\phi$ and approximately 1 cm in z. The $R-\phi$ resolution of the central and forward drift chambers is $150-200\mu m$ while the z resolution of the central drift chamber is around 2 mm. The transition radiation detector provides a pion rejection factor of 50 with electron efficiency of 90%.

The DØ muon detection system consists of five iron toroids, 1.1 to 1.5 meters thick, with a 1.9 T magnetic field, covering polar angles down to $\theta \approx 3°$. Three superlayers of proportional drift tubes measure the track coordinates. The muon detection system has fiducial coverage, apart from small gaps due to detector supports and services, down to $|\eta| = 3.8$. The resolution of the muon detector is given by $\frac{dp}{p} \approx 20\%$ The combined calorimeter and muon thickness is $14\lambda \rightarrow 19\lambda$, resulting in negligible hadronic punchthrough.

At the heart of the DØ detector is the calorimeter. The calorimeter is divided longitudinally into electromagnetic, and fine and coarse hadronic sections. Thin uranium plates initiate showers in the electromagnetic section and the fine hadronic section, and thick copper or stainless steel plates form the passive material in the coarse hadronic section. Liquid argon is used as the active medium for sampling the showers throughout. The calorimeter is divided into three cryostats, for ease of access to the central detectors. In each cryostat, the electromagnetic section is readout in four longitudinal depths, and fine and coarse hadronic sections in 4-5 readout depths. The calorimeter is also finely segmented transversely, with $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ typically, except in the third EM depth (Shower Max) where $\Delta\eta \times \Delta\phi = 0.05 \times 0.05$. In the hadronic layers for $|\eta| > 3.2$ $\Delta\eta \times \Delta\phi$ increases to 0.2×0.2. Readout cells are arranged in semi-projective towers,and calorimetry extends to within 2° of the beamline. The fine segmentation and large coverage results in 47,808 readout channels.

Extensive test beam studies were used to determine energy resolution and linearity of re sponse. Some of the same modules were taken from the test beam to the Tevatron. Energy resolution, based on single e and π studies, was found to be 15% $/\sqrt{E}$ with a 0.5% constant term for electromagnetic showers; and 50% $/\sqrt{E}$ with a 3.8% constant term for hadronic showers.

In the region $0.8 < |\eta| < 1.4$ there is a large amount of uninstrumented material due to the cryostat walls. In order to correct for energy deposits in this material, readout was added in the LAr between the last calorimeter module and the cryostat walls (the "massless gaps"), and a layer of scintillator between the cryostats (the Intercrystat Detctor). The massless gaps and ICD preserve the projective readout of the detector and enhance the energy resolution for jets in this region. As a result of minimal cracks in the calorimeter design, minimal uninstrumented regions, and the ICD/MG readouts, the DØ calorimeter is hermetic, resulting in good $\not{E}_T$ resolution. Figure 2a shows the distribution of the X-component of $\not{E}_T$ measured in minimum bias events in the total scalar E_T bin of 60 GeV $< E_T^{tot} <$ 70 GeV, while figure 2b shows the $\not{E}_T$ resolution as a function of E_T^{tot} . The missing E_T is seen to have a linear dependence on the total scalar E_T . $\not{E}_T$ resolution is 2-4 GeV for E_T^{tot} in the range of 50-150 GeV.

2. New Phenomena Searches with the DØ Detector

2.1. Assumptions for DØ SUSY Searches

All SUSY searches at present are carried out in the framework of the minimal supersymmetric standard model, or MSSM[2]. It is assumed that sparticles are produced in pairs, and that the lightest suspersymmetric particle (LSP) is stable and noninteracting, and so escapes detection. It is also assumed that sparticle decays proceed via cascade decays into lighter sparticles, ending in the LSP.

The MSSM is described by five parameters, which are taken to be the gluino mass ($m_{\tilde{g}}$), the squark mass ($m_{\tilde{q}}$), the Higgsino mass mixing parameter ($\mu = -2m_1$), the ratio of Higgs vacuum expectation values ($\tan\beta$), and the charged Higgs mass (m_{H^+}).

2.2. Search for Squarks and Gluinos

A search for evidence of squark and gluino production is being made, concentrating on the purely hadronic decays at the moment, although it forseen to

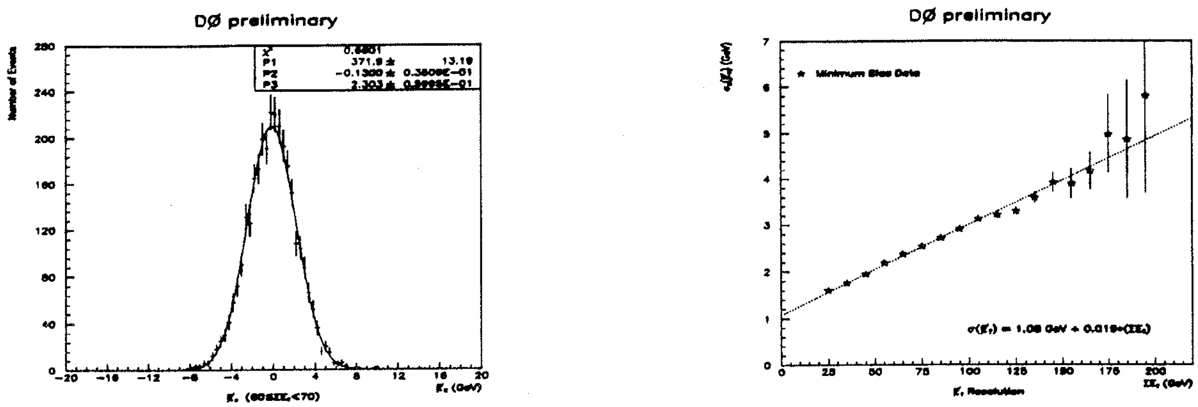


Figure 2: a) The x−component of $\not{E}_T$ in the total scaler E_T bin of 60 GeV $< E_T^{tot} <$ 70 GeV, measured in minimum bias events. b) The $\not{E}_T$ resolution of the DØ detector,as a function of E_T^{tot} .

extend the search to channels with multiple leptons in the final state. The typical search strategy is to look for an excess of events with large missing E_T . However since cascade decays predominate over "direct" decays of a heavy squark or gluino to the LSP, these events are expected to have a softer $\not{E}_T$ spectrum and more (but softer) jets than were looked for in earlier searches[3]. For this reason, the good $\not{E}_T$ resolution of the DØ detector is critical.

Sets of signal events were generated with the ISASUSY[5] generator, with the following MSSM input parameters kept constant

- $\mu = -250$ GeV
- $\tan\beta = 2.0$
- $m_{H^+} = 500$ GeV

and $m_{\tilde{g}}$ and $m_{\tilde{q}}$ varied from 100 GeV to 500 GeV . A total of ten points in the $(M_{\tilde{q}}, M_{\tilde{g}})$ plane were studied for the values of the MSSM parameters $\tan(\beta)$, μ, and M_{H^+} given above. These parameters were chosen to complement the regions of the $(M_{\tilde{g}}, \mu)$ plane indirectly accessible by the experiments at the LEP collider[4].

The standard model backgrounds to a $\not{E}_T$ search include QCD jet events in which the $\not{E}_T$ is faked by mismeasured jets; as well as W+jets events, Z+jets events, and events containing heavy quark semileptonic decays, in which one more neutrinos produce true $\not{E}_T$. Backgrounds were simulated with the ISAJET[6] generator. Both signal and background Monte Carlo events were processed through a detailed simulation of the DØ detector.

Preliminary results have been presented[7] based on 140 nb^{-1} of data. This represent less than 15% of the collider data collected at the time of this workshop report. Events were preselected from this data sample by requiring $\not{E}_T$ $>$ 25 GeV and at least 1 jet (based on a cone of $r = 0.3$) with $E_T > 20$ GeV. There were 4549 events in this sample.

A series of cuts was then applied to this sample in order to remove events with multiple interactions and to ensure unambiguous missing E_T assignments. Events were required to have only one primary vertex and that this vertex be within 40 cm of the beam crossing point. To remove events with an isolated noisy calorimeter cell as well as events with contain one or more electrons, it was required that no calorimeter cluster with $E_T > 20$ GeV and $|\eta| \leq 3.5$ have an electromagnetic E_T fraction $E_T{}^{em}/E_T{}^{total}$ less than 20% or greater than 90%. A total of 92 events passed these requirements.

To select $\tilde{q}$ and $\tilde{g}$ candidate events events were required to have $\not{E}_T > 30$ GeV and at least three jets with $|\eta| \leq 3.5$ and $E_T > 20$ GeV. A total of seven events passed these requirements.

From studies of the Monte Carlo event samples previously described, the dominant background to the multijet + missing E_T signature of $\tilde{q}$ and $\tilde{g}$ events is expected to come from normal QCD multijet events in which one jet is badly mismeasured, producing "fake" missing E_T. In these events the direction in azimuthal angle φ of the missing E_T is correlated with the direction of the jets. After ordering the jets $k = 1, 2, 3$ in decreasing E_T, and defining $\delta\varphi_k$ as the azimuthal angle between jet k and the missing E_T, events were required to have $\sqrt{(\pi - \delta\varphi_1)^2 + (\delta\varphi_2)^2} \geq 0.5$, and $(\pi - \delta\varphi_k) > 0.1$ for $k = 1, 2, 3$. No events remained after all the cuts.

The overall efficiency for $\tilde{q}$ and $\tilde{g}$ events, including detector acceptance, trigger efficiency, and offline cut efficiency varies from 10% to 20% for squark and gluino masses in the range of 100 to 500 GeV. With cross sections calculated by the ISASUSY program, the number of events expected in the data from squarks and gluinos of each mass pair was determined.

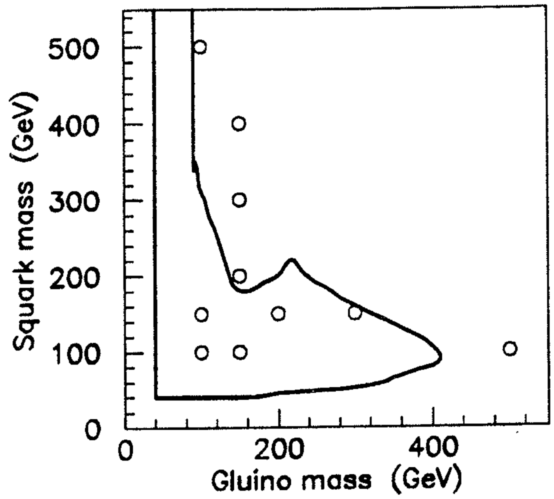
To estimate the effect of systematic errors in the cuts, the jet energy scale of the Monte Carlo was varied by ±10%, and the missing E_T scale was varied by ±15%. A 15% systematic uncertainty in the integrated luminosity was also included. As the cross-sections for $\tilde{q}$ and $\tilde{g}$ production depend on both the choice of q^2 scale and the set of structure functions used, all estimates of production cross-sections were based on the q^2 scale and structure functions which yielded the smallest cross-sections.

The expected number events, with combined systematic and statistical errors, for each gluino/squark mass pair is summarised in the table in figure 3b. The contour plot in figure 3a shows these values in the $m_{\tilde{q}} - m_{\tilde{g}}$ plane, along with the CDF 90% confidence level previously reported[8]. Based on the nonobservation of signal events in this preliminary search, the existence of squarks and gluinos with $M_{\tilde{g}} = M_{\tilde{q}} = 100$ GeV can be ruled out at the 95% confidence level.

2.3. Search for First Generation Leptoquarks

As an example of new phenomena searches outside of the minimal supersymmetric Standard Model, the search for leptoquark prodcution is presented. Leptoquarks are hypothesised to carry both color charge and lepton quantum numbers, and fractional electric charge. For the purposes of the present search, it is assumed that leptoquarks are scalar particles. Leptoquarks often appear in theories based on higher gauge groups (*e.g.* $E(6)$), with or without supersymmetry[9]. They are a natural result of composite models[10], as they represent different combinations of lepton/quark constituents.

Since the leptoquarks carry color, they could be pair-produced in strong interactions at hadron colliders. The pair production cross-section in $p\bar{p}$ collisions is independent of the leptoquarks' unknown Yukawa coupling, which is not the case



$\tilde{g}$ mass	$\tilde{q}$ mass	Number expected
100	100	6.9 ± 2.2
150	100	3.2 ± 0.7
500	100	0.34 ± 0.25
100	150	3.2 ± 1.3
200	150	0.55 ± 0.11
300	150	0.26 ± 0.05
150	200	0.54 ± 0.12
150	300	0.26 ± 0.06
150	400	0.24 ± 0.07
100	500	1.8 ± 0.8

Figure 3: a) The circles in the contour plot indicate the $(M_{\tilde{g}}, M_{\tilde{q}})$ values for the DØpreliminary Monte Carlo event generation. The region enclosed by the contour indicates the CDF 90% confidence level excluded region, from 4.3 pb^{-1} integrated luminosity[7]. b) The table contains the number of events expected in DØ for 0.14 pb^{-1} integrated luminosity, for each of the mass pairs indicated by the circles on the contour plot.

for production at electron-proton colliders such as HERA. One constraint imposed by agreement with low-energy phenomena is that the different leptoquark generations do not mix, so that one expects, for example, pair-production of leptoquarks decaying only to electron/quark or ν_e/quark final states. Possible decay signatures for a first generation leptoquark would then be

- $LQ\bar{L}Q \rightarrow 2e$ + 2 jets;
- $LQ\bar{L}Q \rightarrow 1e$ + 2 jets + $\not{E}_T$;
- $LQ\bar{L}Q \rightarrow$ 2 jets + $\not{E}_T$.

A search for for pair production of scalar leptoquarks, each decaying into electron plus jet, using the DØ detector has been previously reported[11]. The integrated luminosity in this search was 841 nb^{-1} , which represents less than 5% of the total expected for this collider run. The data were taken from a subset of triggers chosen to be analyzed immediately for topical physics results. The triggers of interest for this analysis required either multiple jet towers, or 2 electromagnetic clusters of large transverse energy. There were 1271 events passing these triggers. This offline sample was required to have at least 2 EM clusters (those with 90% of the cluster energy in the EM calorimeter section) with $E_T \geq 20$ GeV , and at least 2 other jets with $E_T \geq 20$GeV . There were 226 events which survived these preliminary requirements. Cuts were then applied to define good leptoquark candidates, as follows:

- The EM energy was computed within 2 cones, of radius 0.4 and 0.2 in η-ϕ space, respectively. Each EM cluster was required to have $E(0.4)-E(0.2) < (15\% \times E(0.2))$.
- There was required to be exactly one central detector track in the road projected from an EM shower center to the vertex. The road had a width in ϕ of

0.1 radians, and in θ of the angle from the shower center to the vertex $\pm$ the error in the vertex (but not less than 0.1 radians).

- The distance of closest approach of the track to the EM shower center was required to be less than 10 cm.

  These three cuts (requiring good, isolated electrons) reduced the sample from 226 to 3 events.

- The energy in the electromagnetic layers was required, for each jet, to be greater than 20% of the total jet energy.

  This cut (requiring clean hardonic jets not due to calorimeter noise) removed 2 of the remaining events.

- Events with the invariant mass of the two electrons consistent with the Z° mass ($70 < M_{ee} < 110$ GeV) were rejected.

The last was used to reject the background from the production of a $Z^\circ \rightarrow e^+e^-$, with 2 associated jets. This cut removed the one remaining event; it is consistent with the Z° + 2 jet hypothesis, having M_{ee} = 82 GeV . A Monte Carlo calculation had predicted 0.3 events of this type for this luminosity.

Other backgrounds which might be expected (Drell-Yan production of 2 electrons away from the Z resonance plus 2 jets, heavy quark decays to electrons) were calculated to be negligible in this sample.

With no events remaining after the 5 cuts, we can set a lower limit on the leptoquark mass. The KMRS-B0 structure functions were used in the ISAJET calculation of the production cross section for squark pairs, with the gluino mass raised to a very large value to suppress irrelevant diagrams. The efficiencies for detection of a leptoquark decaying to electron plus jet was calculated from a full simulation of the detector and triggers, and are summarised in table 1 for 50, 60, 80 GeV mass leptoquarks. For an 80 GeV leptoquark, for example, overall efficiency was calculated to be 9.7%, from the product of a 72% trigger efficiency and a 14% offline selection efficiency. A substantial part of the inefficiency in reconstruction comes from the requirement of 4 objects in the event, each with $E_T \geq 20$ GeV , produced from two particles with mass 80 GeV each.

	LQ mass (GeV)		
	50	60	80
Trigger Eff.	49%	63%	72%
Selection Eff.	3%	10%	14%
Total Efficiency	1.5%	6.3%	9.7%

Table 1: Trigger, offline selection, and total efficiencies for detecting a 50, 60, or 80 GeV leptoquark with the DØ detector.

Systematic errors include an estimated 15% error on the integrated luminosity, 20% (by varying the structure function choice) on the cross section, and 20% on the efficiency calculation. A lower limit on the leptoquark mass is calculated to be M_{LQ} = 74 GeV at the 95% confidence level. This limit is comparable to limits set[12] from SPS collider data and LEP data; but is well below the limit CDF has quoted from its previous run of 4 pb^{-1} . Searches for the other allowed decay mode of the first generation leptoquark (ν_e+ jet) and the signals from a second generation leptoquark (μ+ jet, ν_μ+ jet) are currently underway.

2.3. Wino/Zino and Other SUSY Searches

Another analysis which promises to be of great interest at the Tevatron is the search for production of the lightest chargino and second lightest neutralino ($\tilde{W}_1/\tilde{Z}_2$). As discussed by H. Baer at this workshop, this channel offers a particularly clean multileptonic event signature, with reasonable production cross-section (on the order of 100-1 *pb* for $M_{\tilde{W}_1}$ =47-100 GeV). Thus, a search at the Tevatron can be competitive with the expected search limits for the LEP II experiments; and, for certain model choices (*e.g.*, $SU(5)$ supergravity with $\mu > 0$), a search for $\tilde{W}_1$ up to $M_{\tilde{W}_1} \leq 100$ GeV can be equivalent to a direct gluino search limit of around $M_{\tilde{g}} \leq 400$ GeV [13]. Analyses of the $\tilde{W}_1/\tilde{Z}_2 \to 3e$, $3\mu e + 2\mu$, and $\mu + 2e$ channels are underway.

Although the jets plus missing E_T search for gluinos or squarks offers the greatest reach due to its higher production cross-section, other new phenomena can produce similar event signatures. An adequate determination of the nature of any non-Standard Model physics signal can only be made by combining results from several complementary search channels. Therefore other gluino/squark final states, involving two or more leptons in conjunction with jets and missing E_T , are also being searched.

3. Conclusions

The DØ detector at the Tevatron is online and performing well, during its first data run. Several searches for new phenomena are now well underway, and some preliminary limits have already been set. Already DØ is able to rule out the existence of squarks and gluinos with $M_{\tilde{g}} = M_{\tilde{q}} = 100$ GeV at the 95% confidence level, based on only 140 nb^{-1} ; and the existence of first generation leptoquarks up to $M_{LQ} = 74$GeV at 95% confidence level, based on only 840 nb^{-1} . DØ is expected to record nearly 20 pb^{-1} by the mid-run shutdown in June, 1993. For the whole of the first Tevatron run, DØ hopes to collect 100 pb^{-1} . At the time of this report, over 11 pb^{-1} had been collected and were being analyzed. These and other new phenomena searches will continue, as more data is collected and detector systematics, luminosity values, and background levels are better understood.

4. Acknowledgements

I would like to thank Dr. Pran Nath and the organizers of the SUSY93 workshop for the invitation to speak on behalf of the DØ collaboration. I would like to thank my colleagues on DØ for the hard work put into the current successful first run of the detector, as well as for the opportunity to present these results at the SUSY93 workshop.

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