Direct Accelerator Searches for Supersymmetry

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This paper reviews some of the recent results on the search for supersymmetry at the Tevatron and HERA collider experiments. The results from Tevatron are based the data from $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. The results from HERA are based on the data from e^+p and e^-p collisions at $\sqrt{s} = 318$ GeV.

1. INTRODUCTION

The Standard Model (SM) has been remarkably successful and supported by experiments over the past decades. Its predictions have been tested to very high accuracy, and all the particles predicted by the SM have been found, except the Higgs boson. Given its success, however, the SM is not a complete theory. It cannot explain the mechanism behind the electroweak symmetry breaking, no accounting for gravity, no prediction on the unification of the gauge couplings at high energy scale, and recent cosmological observation indicates that the SM particles only account for $\sim 4\%$ of the matter of the universe. Therefore extensions to the SM have been constructed to make the theory more complete. Some of these extension models include Supersymmetry (SUSY), Grand Unified Theory (GUT), and Extra Dimensions. These extensions predict signs of new physics are very rare.

Supersymmetry [1] overcomes some of the theoretical problems in the SM by introducing a symmetry between the fermions and bosons. Every boson (fermion) will have a fermion (boson) associated to it. In minimum supersymmetric Standard Model (MSSM) a scalar supersymmetric partner is assigned to every SM fermion, and a fermionic superpartner to every SM boson. A second Higgs doublet (with its superpartner) is also introduced so as to provide masses to the up-type and down-type quarks. When the symmetry is not broken, the SM particles and the superpartners to these particles share the same quantum numbers except spin. However when the symmetry is broken, the masses of the SM particles and its superpartner are no longer the same.

In SUSY the gravitational force can be unified with the other three fundamental forces (strong, weak, electromagnetic) by making SUSY to be a local gauge symmetry. This leads to the supergravity theory, called SUGRA. According to SUGRA, the breaking of the symmetry in SUSY occurs in a "hidden" sector that is neutral with respect to the SM gauge group. This information of symmetry breaking is mediated, via gravitational interactions, to the "visible" sector that contains the MSSM. There are over a hundred of parameters in SUGRA. However in the minimum SUGRA (mSUGRA) scenario the numbers of parameters are reduced to four plus one sign. It assumes that at the Planck or GUT scale all scalars have a common mass m_0, all gauginos have a common mass $m_{1/2}$, and all trilinear couplings have a common value A_0. The absolute value of the Higgsino mass parameter μ can be determined by demanding the correct electroweak symmetry breaking. All the masses of the SUSY particles can be expressed as functions of soft SUSY breaking parameters, which can be written in terms of m_0, $m_{1/2}$, A_0, $\tan\beta$, and sign(μ) ($\tan\beta$ is the ratio of the two Higgs vacuum expectation values). In the case of Gauge Mediated Supersymmetry Breaking (GMSB), the breaking of the symmetry in SUSY is mediated to the "visible" sector via gauge interactions.

Under the MSSM framework every particle is assigned with a quantum number called R-parity (Rp). The particles of the SM are Rp even (Rp=1), whereas their corresponding superpartners are Rp odd (Rp=-1). In MSSM Rp is not required to be conserved. However its conservation is invoked in order to overcome problems stemming from Flavor Changing Neutral Current (FCNC) and proton decay. Lepton number or baryon number is no longer conserved when Rp is violated. The Rp violating superpotential is

$$W_{\not{R}} = \frac{1}{2}\lambda_{ijk}L_iL_jE^c_k + \lambda'_{ijk}L_iQ_jD^c_k + \frac{1}{2}\lambda''_{ijk}U^c_iD^c_jD^c_k + \mu_iL_iH_u, \tag{1}$$

where L_i and Q_i are SU(2)-doublet lepton and quark superfields respectively. E^c_i, U^c_i, D^c_i are SU(2)-singlet charged lepton, up and down quark superfields respectively. H_u is the Higgs superfield which is responsible for generating the masses of the up type quarks. λ, λ' (λ'') are the Rp violating coupling constants for the case of lepton (baryon) number violation. The constraints from FCNC and proton decay put tight limits on some of these Rp violating coupling constants. The limits from proton decay prevents the simultaneous occurrence of both lepton and baryon number violation in a Rp violating process.

1.1. Phenomenology of SUSY

If Rp is required to be conserved, then in a colliding experiment the SUSY particles can only be produced in even numbers. The heavy SUSY particles will decay into lighter SUSY and SM particles. However the lightest SUSY particle (LSP) would have to be stable. If the LSP is electrically neutral, then it can be a prime dark matter candidate. This particle would not be detected in the experiment, and results in the appearance of missing transverse energy ($\not\!\!E_T$) seen by the experiment.

If Rp is not conserved, single SUSY particle can be produced in the colliding experiment, which may result in larger production rates of SUSY particles, as compared to the Rp conserved case. The LSP would not be stable and could decay into SM particles, and thus not a dark matter candidate. The final states of the colliding events would not always have the signature of large $\not\!\!E_T$, and that it would tend to contain more leptons and jets, as compared to the Rp conserved case.

In the general MSSM there are more than 100 parameters. This leads to the difficulty of the theory to make predictions. In order to overcome this problem, some models make certain assumptions about the breaking of the symmetry to reduce the number of unknown parameters in the theory. Different models make different kinds of assumptions, thus the predictions would depends on which model one chooses. The common models used in the experimental high energy physics are mSUGRA and GMSB. These models serve as a common bench mark in order for different collider experiments to compare their results. In mSUGRA, the LSP is the lightest neutralino ($\tilde{\chi}_1^0$). In the case of GMSB, the LSP is the gravitino ($\tilde{G}$), which has a predicted mass of $\sim O(1)$ keV. The phenomenology under this model is very much determined by which SUSY particle is the next-to-lightest SUSY particle (NLSP).

1.2. Experimental Results from Direct Accelerator Searches for SUSY

This paper covers recent experimental results on searches for SUSY from the Tevatron experiments and the HERA experiments.

There are two colliding experiments at the Tevatron, CDF and DØ . Detailed description of the Tevatron accelerator and the two experiments are described in the talk by Scott S. Snyder at this conference [2].

The HERA accelerator, located in Hamburg, Germany, collides an electron or positron beam of 27.5 GeV with a proton beam of 920 GeV (820 GeV until 1997), yielding center-of-mass energy ($\sqrt{s}$) of 318 GeV (300 GeV). The two collider experiments are H1 and ZEUS. Detailed description of the H1 and the ZEUS detectors can be found in [3, 4].

In the first part of this paper we present results on SUSY searches in which Rp is assumed to be conserved. In the second part of the paper we present search results whereby the Rp quantum number is violated. The results from CDF and DØ are based on data collected from $p-\bar{p}$ collisions at $\sqrt{s}=1.96$ TeV.

2. SEARCHES FOR SUSY (R-PARITY CONSERVED)

2.1. Searches for Squarks and Gluinos in Missing Transverse Energy and Jets

At the Tevatron squarks and gluinos can be copiously produced. They will decay into SM particles and, possibly through cascades, into LSPs. Assuming that Rp is consevred, the LSP will be stable. If the LSP is electrically neutral, then it will escape detection and the final state in the squarks and gluino production will have a signature of multiple jets and large $\not\!\!E_T$. In mSUGRA models, the LSP candidate is the lightest neutralino $\tilde{\chi}_1^0$. DØ has performed a direct search for squarks and gluino with a data sample of 85 pb^{-1} [5]. These events are selected by requiring at least two energetic jets ($E_{T1} > 60$ GeV, $E_{T2} > 50$ GeV, where E_{T1} and E_{T2} are the transverse energy of the first two leading jets) and large $\not\!\!E_T$ ($\not\!\!E_T > 175$ GeV). The jets should be acoplanar, and not pointing in the same direction as the $\not\!\!E_T$ in the transverse plane. The sum of the transverse energies of all the jets in the event (H_T) should be $H_T > 275$ GeV. After applying all the selection cuts, four events survived in the data sample, and the expected number of SM background events is 2.67 ± 0.95(stat.). The SM backgrounds are mainly from $Z(\to \nu\nu)$+jets and $W(\to \tau\nu)$+jets processes. The $\not\!\!E_T$ distribution of the selected data events, with a lower $\not\!\!E_T$ cut of $\not\!\!E_T > 45$ GeV, is compared to the expectation from SM processes (without QCD multi-jet) in Figure 1. Among the four selected data events, the highest $\not\!\!E_T$ event has $\not\!\!E_T = 381$ GeV, which is well balanced against two leading jets of $E_{T1} = 289$ GeV, and $E_{T2} = 117$ GeV. These results are being interpreted in the mSUGRA scenario using $m_0 = 25$ GeV/c^2, $\tan\beta = 3$, $A_0 = 0$, and $\mu < 0$. The 95% confidence level (C.L.) limit on the squark and gluino production cross section as a function of the gluino mass is shown in Figure 2. The new DØ preliminary results exclude gluino (squark) mass below 333 GeV/c^2 (292 GeV/c^2), which corresponds to excluding all $m_{1/2}$ values below 131 GeV/c^2 for $m_0 = 25$ GeV/c^2. This new result has extended Run I limit [6].

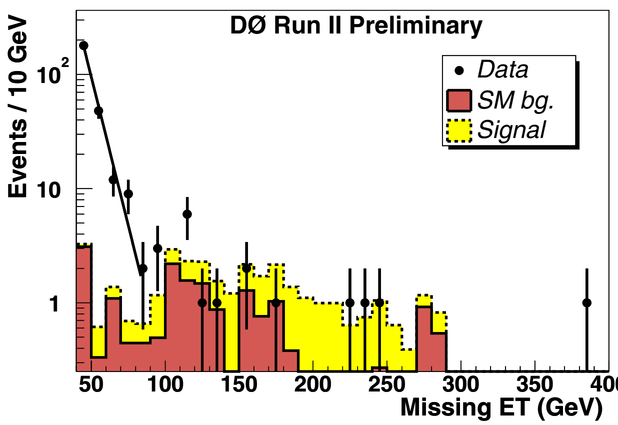

Figure 1: The $\not\!\!E_T$ distribution of the selected events after all cuts, except the final cut on the $\not\!\!E_T$ for the search of squarks and gluino by DØ .

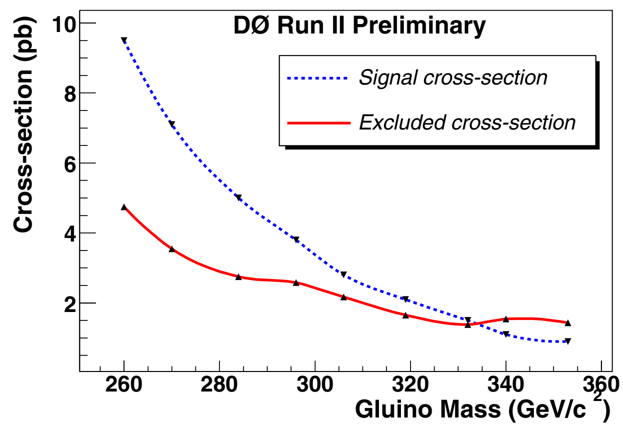

Figure 2: The 95% confidence level (C.L.) limit on the squark and gluino production cross section as a function of the gluino mass for $m_0 = 25$ GeV/c^2, $A_0 = 0$, $\tan\beta = 3$, and $\mu < 0$.

2.2. Searches for Sbottom from Gluino Decays

The mass eigenstates of scalar SUSY particles are a mixture of their weak eigenstates. The amount of mixing depends on a few parameters ($\tan\beta$, mass of SM partner, trilinear coupling of the Higgs to the SUSY particle) of the theory. In the sbottom sector there can be a large mass splitting between the two sbottom mass eigenstates at high $\tan\beta$ such that one of the sbottom ($\tilde{b}_1$) is light enough to be in the reach at the Tevatron.

At CDF, we search for gluino pair production $p\bar{p} \to \tilde{g}\tilde{g}$, where the gluino decays to $\tilde{g} \to b\tilde{b}$, and then followed by the subsequent sbottom decays to a b quark and the lightest neutralino $\tilde{\chi}_1^0$ ($\tilde{b} \to b\tilde{\chi}_1^0$) [7]. If $\tilde{\chi}_1^0$ is the LSP and stable (Rp conserved), then the decay signature of this process will be 4 b jets and large $\not\!\!E_T$. A diagram of the pair production of gluinos and its subsequent decays, is shown in Figure 3.

The search is performed on a data sample of 156 pb^{-1} by selecting events with $\not\!\!E_T > 80$ GeV, no isolated charged leptons (e, μ), and at least one jet to be tagged as a b jet (the vertex reconstructed from the tracks within the jet is displaced from the event primary vertex). The large $\not\!\!E_T$ cut reduces the contribution from QCD multi-jet process, whereas the isolated charged lepton veto and heavy-flavor tagging reduce the contributions from electroweak processes (W+jets, Z+jets, and diboson). After applying all selection cuts, 21 events are observed with 16.4 ± 3.63

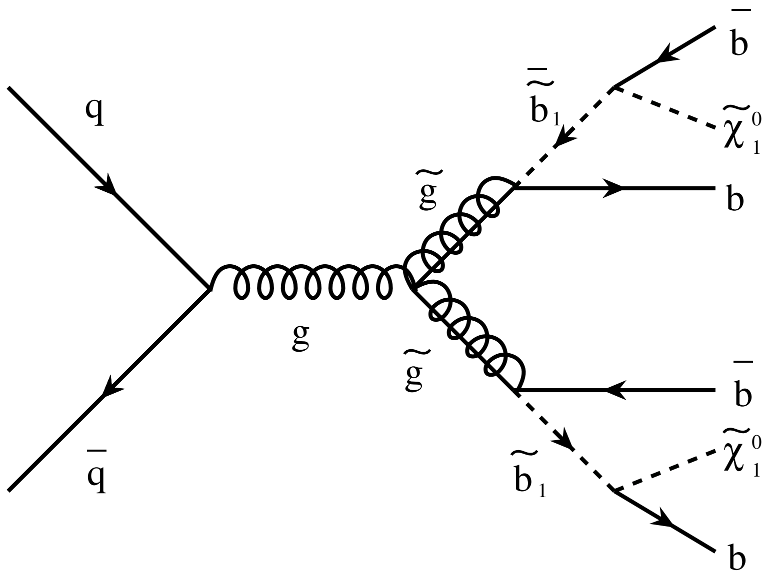

Figure 3: A diagram of the pair production of gluinos and its subsequent decays.

events expected from SM processes for the case of exclusive single b tagged (only one jet tagged as a b jet). For the case of inclusive double b tagged (two or more jets tagged as a b jets), four events are observed, and we expect 2.63 ± 0.70 events from SM processes. Figure 4 compares the $\not\!\!E_T$ distribution between data and SM expectation for exclusive single b tagged events and inclusive double b tagged events. A lower $\not\!\!E_T$ cut is applied for the comparison. As no excess of events is observed in the data, these results are used to obtain a 95% C.L. exclusion region in the kinematic plane of sbottom mass as function of the gluino mass, which is shown in Figure 5. The new Run II results have greatly extended the CDF Run I limit.

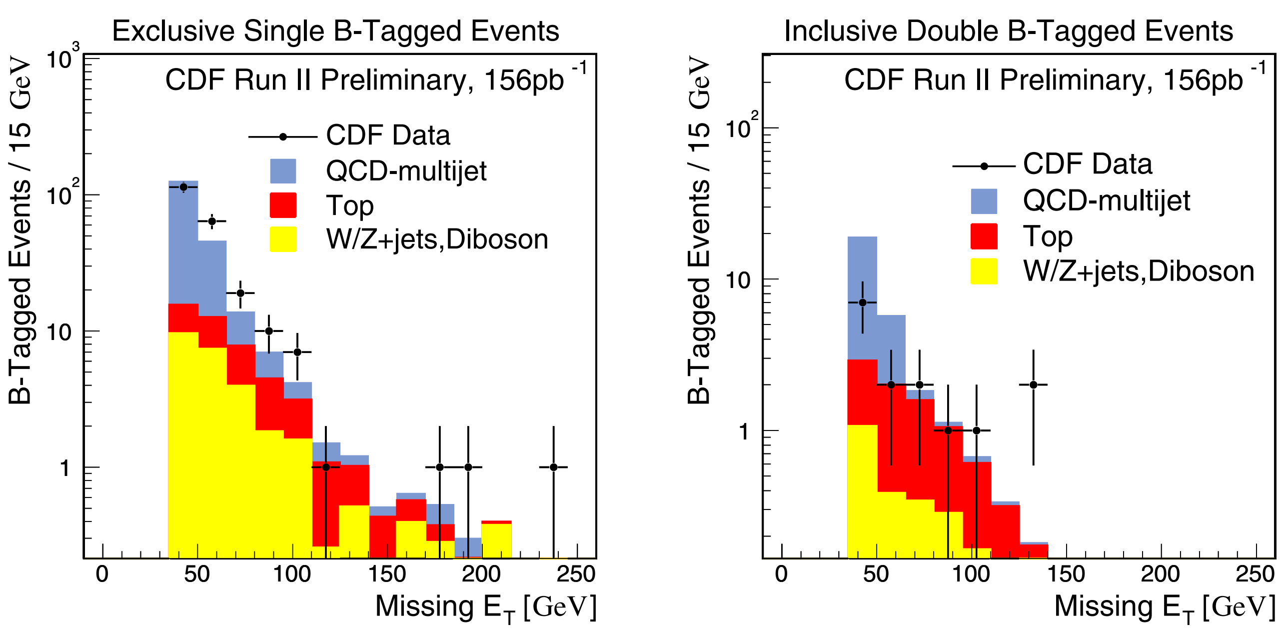

Figure 4: The $\not\!\!E_T$ distribution for (left) exclusive single b tagged events and (right) inclusive double b tagged events. All selection cuts have been applied except the final cut on the $\not\!\!E_T$ for the search of sbottom quark in gluino pair production by CDF.

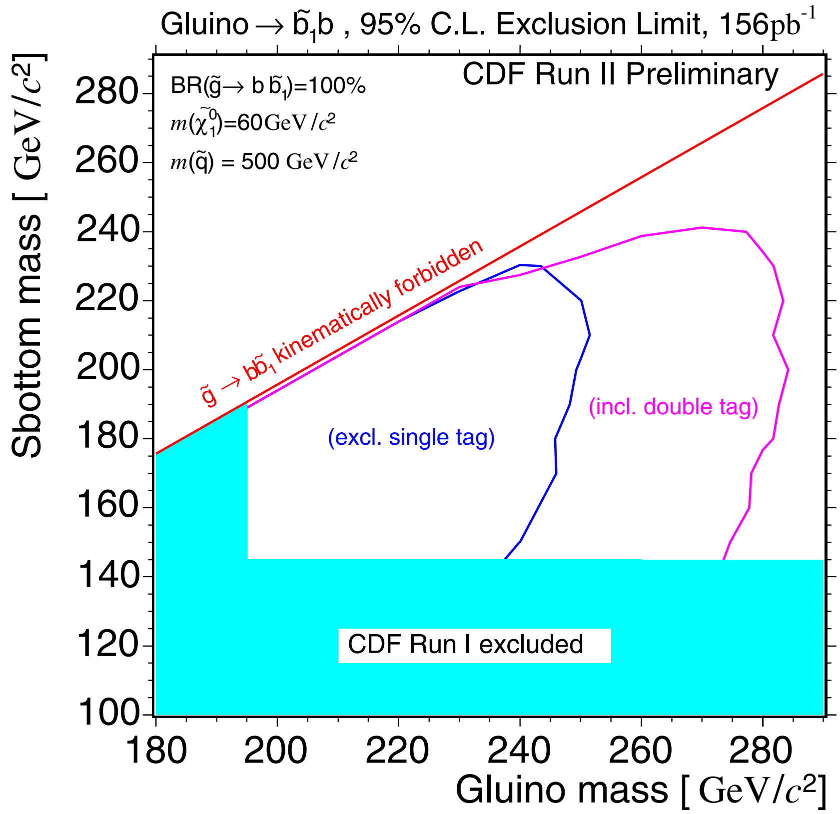

Figure 5: The 95% C.L. exclusion contours in the $m_{\tilde{g}}$ and $m_{\tilde{b}}$ plane.

2.3. Searches for Associated Production of Chargino and Neutralino in Multi-lepton Final State

The decays from associated production of chargino and neutralino, which are the charged and neutral superpartners of the electroweak gauge and Higgs bosons, can result in multiple leptons and large $\not{E}_T$ in the final state. At hadron colliders the rate of producing leptons in the final state from SM processes is small. Therefore the search for SUSY in multi-lepton final state will have small background contribution from the SM processes, thus making this an ideal channel to search for new physics. The DØ experiment has performed searches for associated production of the lightest chargino ($\tilde{\chi}_1^{\pm}$) and the next-to-lightest neutralino ($\tilde{\chi}_2^0$) in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV [8]. The search focuses on the channels where both $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ decay into leptons and LSP ($\tilde{\chi}_1^0$). In this analysis the LSP is assumed to be stable and escapes detection. Figure 6 shows two possible decay modes of the $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ that leads to multi-lepton and large $\not{E}_T$ in the final state. The final states of the channels included in this search are :

- $e + e +$ lepton (lepton: isolated track)
- $\mu + \mu +$ lepton (lepton: isolated track)
- $e + \mu +$ lepton (lepton: isolated track)
- like-sign di-muon

The search is optimized in a specific mSUGRA parameter space ($\tan\beta = 3$, $A_0 = 0$, $\mu > 0$, $72 < m_0 < 88$ GeV/c^2, and $165 < m_{1/2} < 185$ GeV/c^2), in which the corresponding chargino mass is in the range $100 < M_{\tilde{\chi}_1^{\pm}} < 115$ GeV/c^2, and has high leptonic branching ratio for the decays of both $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$. The data sample used for this search ranges

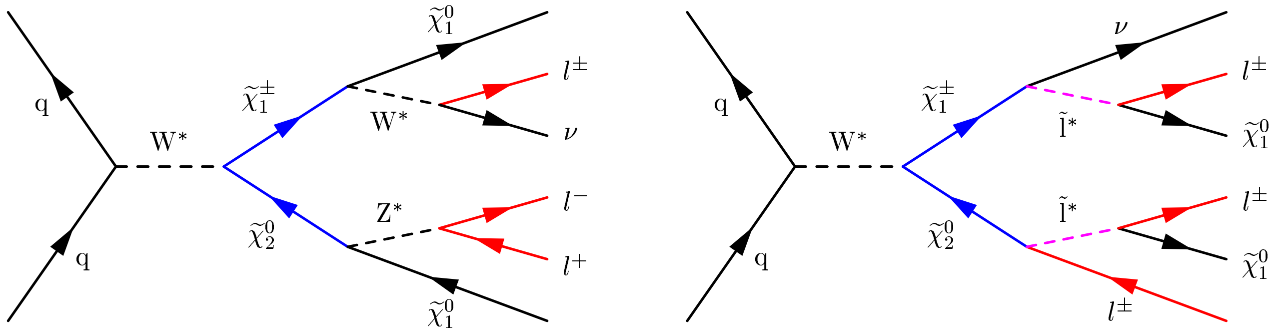

Figure 6: The associated production of the lightest chargino ($\tilde{\chi}_1^\pm$) and the next-to-lightest neutralino ($\tilde{\chi}_2^0$), and its decays that leads to multi-lepton and large $\not\!\!E_T$ in the final state.

from $\sim 150 - 250$ pb^{-1}, depending on the channel of the analysis. Each analysis channel requires two charged leptons, an isolated track (expect like-sign di-muon channel), and $\not\!\!E_T \gtrsim 20$ GeV. After applying all the selection cuts, the number of observed events in the data for each channel ranges from 0 to 1, and are in good agreement with the expected SM contributions. Table I summarizes the selection cuts and results from each channel.

Table I: Summary of the selection cuts for the four DØ multi-lepton analyses on the search for associated production of chargino and neutralino. Also listed in the table are the number of observed events, the expected SM events, and the sources of the dominant SM background, after applying all section cuts.

Channel	eel	$e\mu l$	$\mu\mu l$	Like-sign $\mu\mu$
Lumi. data sample (pb^{-1})	249	235	221	147
p_T of two charged leptons (GeV/c)	$p_T(e1) > 12$) $p_T(e2) > 8$	$p_T(e) > 12$) $p_T(\mu) > 8$	$p_T(\mu 1) > 15$) $p_T(\mu 2) > 5$	$p_T(\mu 1) > 10$) $p_T(\mu 2) > 5$
Isolated Track p_T (GeV/c)	> 3	> 5	> 3	
$\not\!\!E_T$ (GeV)	> 20	> 20	> 22	> 15
$\not\!\!E_T \times p_T^{\text{isotrack}}$ (GeV^2/c)	> 250	> 100		
Invariant mass cut	Z veto	W+jets veto	Z veto	Z veto
Other cuts	cuts specific to each analysis			
# Observed Events	1	0	1	1
# Expected Events	0.68 ± 0.51	0.29 ± 0.33	1.83 ± 0.45	0.13 ± 0.63
Dominant SM Background	$\gamma^*/Z \to e^+e^-$ $W+\gamma$ WW/WZ	WZ $W+\gamma$ $W+$jets	$\gamma^*/Z \to \mu^+\mu^-$ $\gamma^*/Z \to \tau^+\tau^-$	WZ $b\bar{b}$ ZZ

The results from all the four channels are combined to obtain the upper limit, at 95% C.L., the total cross section times branching ratio for associated production of chargino and neutralino with multi-lepton final state. The upper limit cross section times branching ratio as function of the chargino mass is shown in Figure 7. The limit set by this search is a significant improvement over the DØ Run I results [9] and CDF Run I results [10]. By comparing the measured upper limit cross section with the cross section from the specific mSUGRA model that is used in this analysis, DØ is able to exclude chargino ($\tilde{\chi}_1^\pm$) mass below 97 GeV/c^2. If the measured upper limit cross section is compared to the cross section of the heavy squark model (high squark masses, low slepton masses), chargino mass below 111 GeV/c^2 would be excluded.

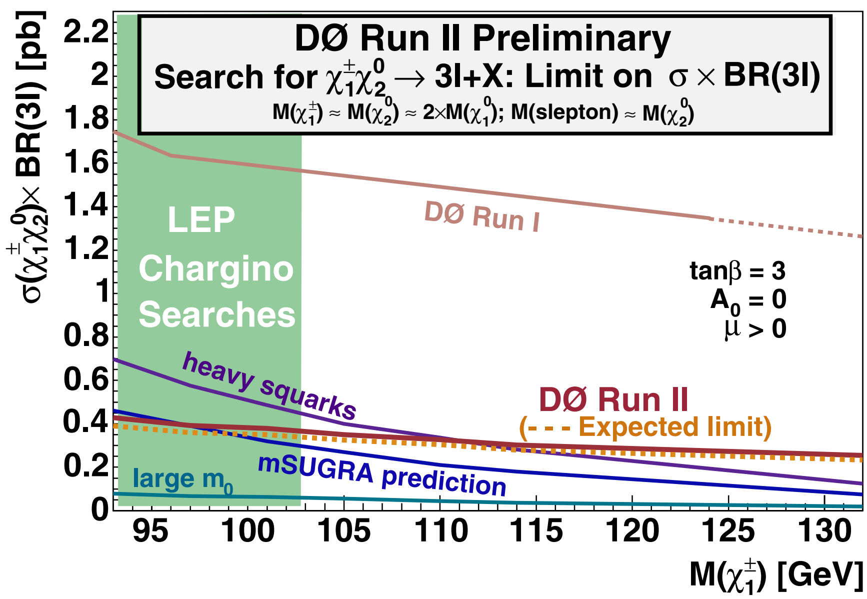

Figure 7: The 95% C.L. upper limit on the cross section times branching ratio for associated chargino and neutralino production with leptonic final states measured by DØ . The three curves represent models with "heavy quarks", "mSUGRA", and "large m_0".

2.4. Search for GMSB SUSY in $\gamma\gamma + \not\!\!E_T$

In the extended GMSB models, the LSP is the gravitino $\tilde{G}$. In the case where the $\tilde{\chi}_1^0$ is the NLSP, it can decay to a $\tilde{G}$ by emitting a photon ($\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$). The $\tilde{G}$ is neutral and interacts weakly, thus escapes detection. If *Rp* is conserved, this means that at least two $\tilde{\chi}_1^0$ will be produced, and there will be at least two photons plus large $\not\!\!E_T$ in the final state. The DØ analysis [11], based on Run II data sample of 263 pb^{-1}, required two central photons ($|\ \eta\ | < 1.1$) with $E_T > 20$ GeV. From the study of optimizing the signal over background, the $\not\!\!E_T > 40$ GeV region is chosen for the limit calculation. For this region two events are observed in the data, and the number of SM background events is 3.7 ± 0.6. The background is mainly from SM processes with mis-identified photons and/or mis-measured $\not\!\!E_T$. For background with no inherent $\not\!\!E_T$, the SM processes are QCD multi-jets (with jets mis-identified as photons), direct photon production, and from $\gamma^*/Z \rightarrow e^+e^-$ (with both electrons mis-identified as photons). For background with real $\not\!\!E_T$, the SM processes are $W(\rightarrow e\nu) + \gamma$, $W +$ jets, $Z \rightarrow \tau^+\tau^- \rightarrow e^+e^- + X$, and $t\bar{t}$ productions. In this case the electrons (from the decay products) and the jets are mis-identified as photons. Figure 8 shows the $\not\!\!E_T$ distribution of the events after applying all the selection cuts except the cut in the $\not\!\!E_T$. Using the values for the GMSB parameters of $M_m = 2\Lambda$, $N_5 = 1$, $\tan\beta = 15$, and $\mu > 0$, the 95% C.L. upper limit on the GMSB cross section vs Λ is shown in Figure 9. Λ is the SUSY breaking scale parameter, M_m is the messenger mass scale, N_5 is the number of messenger fields, and μ is the Higgsino mass parameter. The derived limit on Λ is $\Lambda > 79.6$ TeV, which corresponds to $M_{\tilde{\chi}_1^0} > 107.7$ GeV/c^2, and $M_{\tilde{\chi}_1^\pm} > 194.9$ GeV/c^2.

The CDF experiment has also performed a similar search in $p\bar{p}$ collisions using a data sample of 202 pb^{-1} [12]. It requires two central photons ($|\ \eta\ | < 1.0$) with $E_T > 13$ GeV, and the transverse missing energy satisfies the cut $\not\!\!E_T > 45$ GeV. After applying all the selection cuts, no event is observed in the data, and expected 0.27 ± 0.12 background events, with 0.15 ± 0.08 events from the SM processes, and 0.12 ± 0.09 events from beam-related and cosmic rays background. Using the same values for the GMSB parameters as the DØ experiment, CDF sets the 95% C.L. limit on Λ to be $\Lambda > 69$ TeV, $M_{\tilde{\chi}_1^0} > 93$ GeV/c^2 and $M_{\tilde{\chi}_1^\pm} > 167$ GeV/c^2. The $\not\!\!E_T$ distribution of the selected events (without the $\not\!\!E_T$ cut) of this analysis is shown in Figure 10. The 95% C.L. upper limit on the GMSB cross section vs chargino mass is shown in Figure 11.

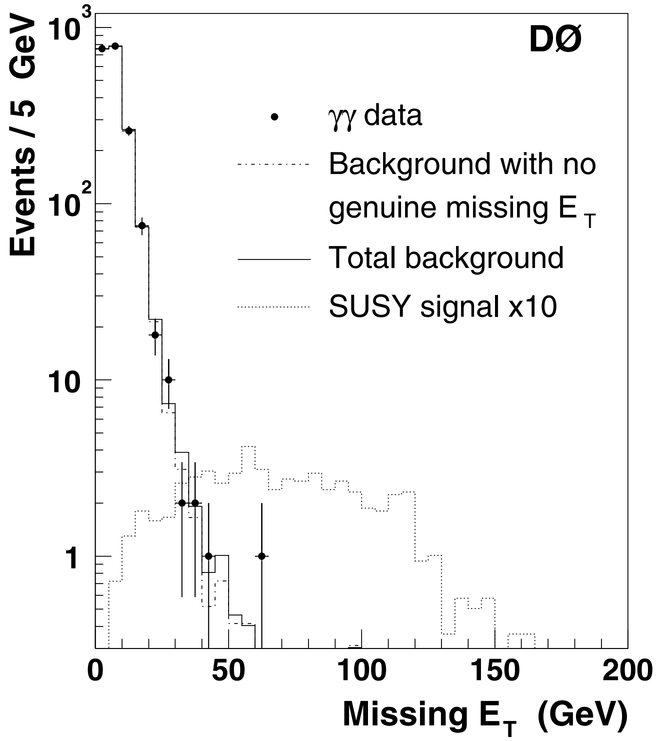

Figure 8: The $\not\!\!E_T$ distribution of the selected events after all cuts, except the final cut on the $\not\!\!E_T$ for the search of GMSB SUSY in $\gamma\gamma + \not\!\!E_T$ signature by DØ .

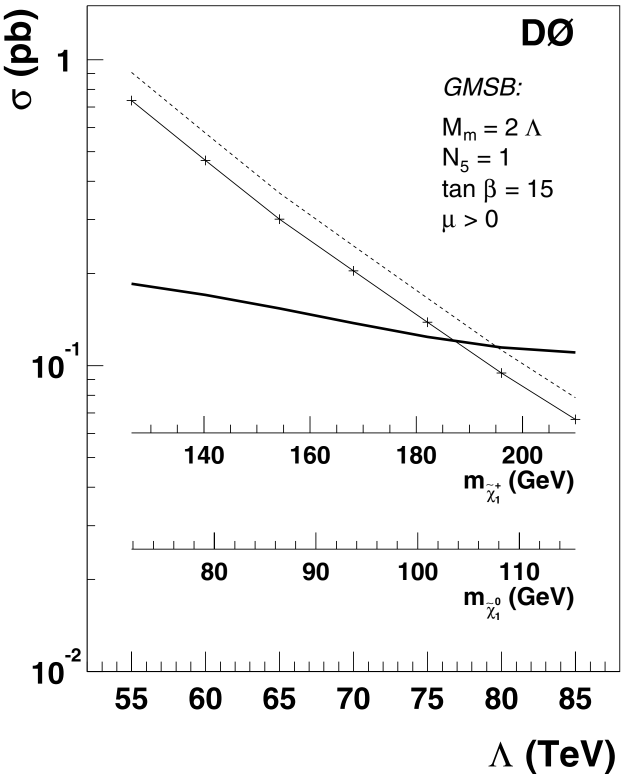

Figure 9: The 95% C.L. limit on the GMSB cross section (solid line) as a function of the SUSY breaking scale parameter Λ. Also shown in the plot are the theoretical cross sections. The leading order cross section (LO) is indicated by a thin solid line with crosses. The next-to-leading order cross section (multiplied by a K factor ~ 1.2 on the LO cross section) is indicated by a thin dashed line).

3. SEARCHES FOR SUSY (R-PARITY VIOLATION)

3.1. Search for SUSY with R-Parity Violation in the Tri-lepton Final States

At the Tevatron supersymmetric particles can be pair produced and decay into pairs of the lightest neutralino. If Rp violation (RPV) processes are allowed, then the neutralino ($\tilde{\chi}_1^0$) can decay into SM particles. If only the RPV coupling λ_{121} is non-zero, the final state from the decay of a pair of neutralinos will consist of four charged leptons, with at least two electrons. The diagram of this decay process is shown in Figure 12. If only the RPV coupling λ_{122} is non-zero, the final state will consist of four charged leptons, with at least two muons. As the rates of SM processes in $p\bar{p}$ collisions with multi-leptons in the final states are small, the search for SUSY in the multi-lepton signature will have small background contributions from the SM processes.

In Run II DØ has performed searches for supersymmetry in $p\bar{p}$ collisions, under the hypothesis that Rp is violated either via λ_{121} coupling only, or via λ_{122} coupling only. For the search involving λ_{121} [13], the analysis, which is performed on a data sample of 238 pb^{-1} of integrated luminosity, requires at least two electrons in the final state. The third charged lepton can be either an electron or a muon. These three leptons should be well isolated from each other. Events with reconstructed di-electron mass of $80 < M_{ee} < 100$ GeV/c^2 are removed to reject contribution from the Z boson production. The missing transverse energy is required to be greater than 15 GeV (which comes

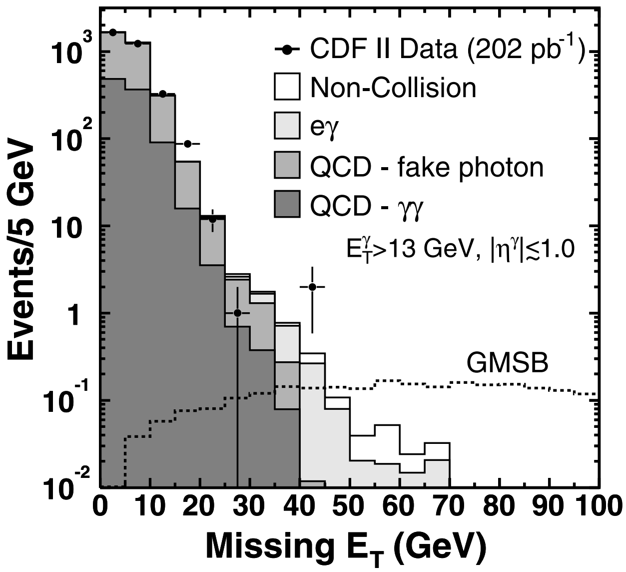

Figure 10: The $\not\!\!E_T$ distribution of the selected events after all cuts, except the final cut on the $\not\!\!E_T$ for the search of GMSB SUSY in $\gamma\gamma + \not\!\!E_T$ signature by CDF.

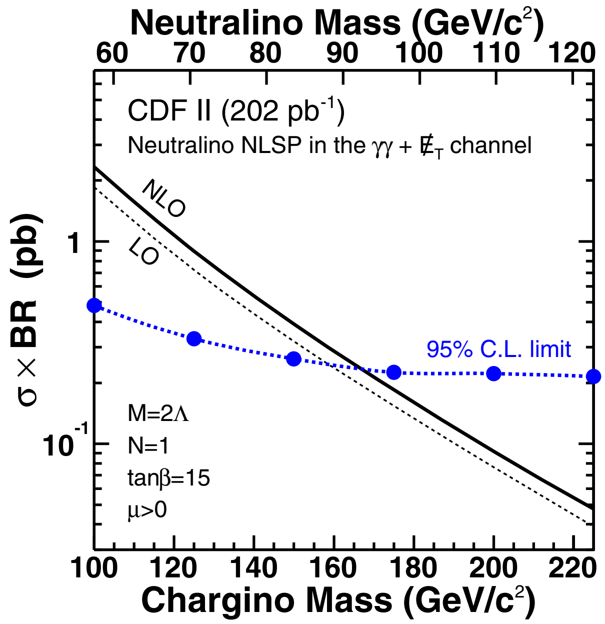

Figure 11: The 95% C.L. limit on the $\chi_1^\pm\chi_2^0$ cross section (dashed line with solid circles) as a function of the chargino mass in the GMSB models. Also shown in the plot are the theoretical cross sections. The leading order cross section (LO) is indicated by a thin dashed line. The next-to-leading order cross section is indicated by a solid line.

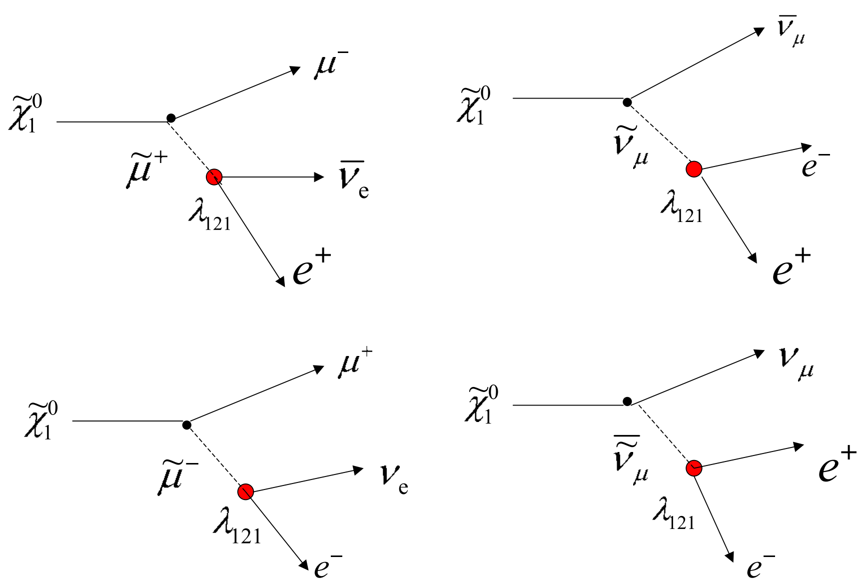

Figure 12: The Rp violation decay of neutralino through the λ_{121} coupling.

from the neutrinos in the signal final state). After applying all the selection cuts, no data event is selected, and expect 0.45 ± 0.43 events from SM processes. The dominant sources of SM contributions are from $\gamma^*/Z \to e^+e^-$ and $\gamma^*/Z \to \tau^+\tau^-$ productions.

For the search involving λ_{122} coupling [14], at least two muons are required to be found in the final state. These two muons should originate from the same interaction point, and be well separated from each other, and from jets. A cut in the $M_{inv} - \not{E}_T$ plane (M_{inv} is the invariant mass of the first and second leading muons) is used to reduce the SM contributions from γ^*/Z, Υ, and QCD multi-jet productions. An azimuthal separation of $\Delta\phi(\mu_1, \mu_2) < 2.6$ radian is required on the two leading muons to further reduce contribution from γ^*/Z production. After applying the above cuts, a third lepton (electron or muon) is required and it should originate from the same interaction point as the two leading muons. The third lepton should be well separated from jets. The size of the data sample used for this analysis is 160 pb^{-1} of integrated luminosity. With all the selection cuts applied, two events are observed in the data, and we expect 0.63 ± 1.93 events from SM processes. The dominant sources of SM contributions are from $\gamma^*/Z \to \mu^+\mu^-$ and $\gamma^*/Z \to \tau^+\tau^-$ productions.

The results from the two RPV SUSY searches are interpreted in the framework of mSUGRA model for different sets of parameters (m_0, $m_{1/2}$, $\tan\beta = 5$, $A_0 = 0$, and both signs of the higgsino mass parameter μ). The 95% C.L. upper limits on the SUSY cross section for $m_0 = 250$ GeV/c^2, and positive μ are shown in Figure 13. Table II summarized the 95% C.L. exclusion limit on the SUSY parameter $m_{1/2}$ for both positive and negative signs of μ. The new DØ Run II preliminary results have significantly improved the Run I limits.

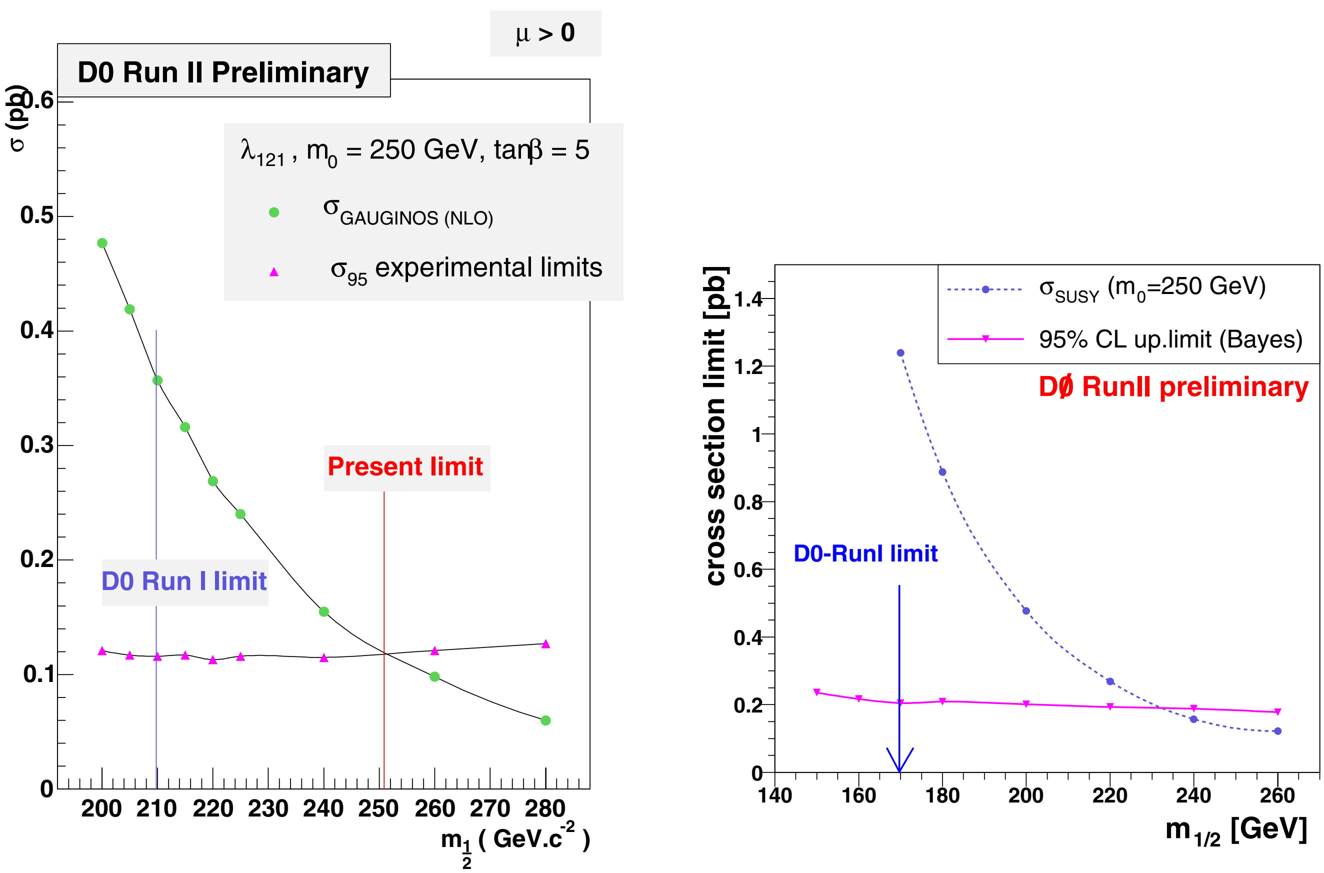

Figure 13: The 95% C.L. upper limits on the SUSY cross section as function of $m_{1/2}$ for $m_0 = 250$ GeV/c^2, and positive μ. (left) *Rp* violation decay via λ_{121} coupling. (right) *Rp* violation decay via λ_{122} coupling.

Table II: The 95% C.L. exclusion limit on the SUSY parameter $m_{1/2}$ for both positive and negative signs of μ on the search for SUSY with Rp violation in the tri-lepton final states by DØ .

RPV coupling	λ_{121}	λ_{122}
$\mu < 0$	$m_{1/2} < 231$ GeV/c^2	$m_{1/2} < 205$ GeV/c^2
$\mu > 0$	$m_{1/2} < 251$ GeV/c^2	$m_{1/2} < 230$ GeV/c^2

3.2. Search for Resonant Slepton Production

The Rp violating extension of the MSSM offers the opportunity for single production of SUSY particles. At Tevatron, a sneutrino ($\tilde{\nu}$) or a charged slepton ($\tilde{l}$) can be produced in resonance via the λ'_{ijk} couplings.

In Run II the DØ experiment has searched for the resonant production of a smuon ($\tilde{\mu}$), assuming that the Rp violating coupling λ'_{211} is non-zero and all other Rp violating couplings are negligibly small [15]. The $\tilde{\mu}$ decays into a muon and a neutralino, and the neutralino decays into a muon and two quarks. The final state contains two muons and two jets. The resonant production and decay of $\tilde{\mu}$ in $p\bar{p}$ collision is shown in Figure 14. The search is performed on a data sample of 154 pb^{-1} of integrated luminosity. Events are selected with two muons and two jets in the final state, and the muons and jets are well separated from each other. The invariant mass of the two muons and two jets ($M_{\tilde{\mu}}$), and the invariant mass of the second leading muon and two jets are reconstructed. Cuts on the mass windows of the reconstructed invariant masses are applied to enhance the signal over the SM background. The selection cuts are optimized separately for different SUSY parameter points.

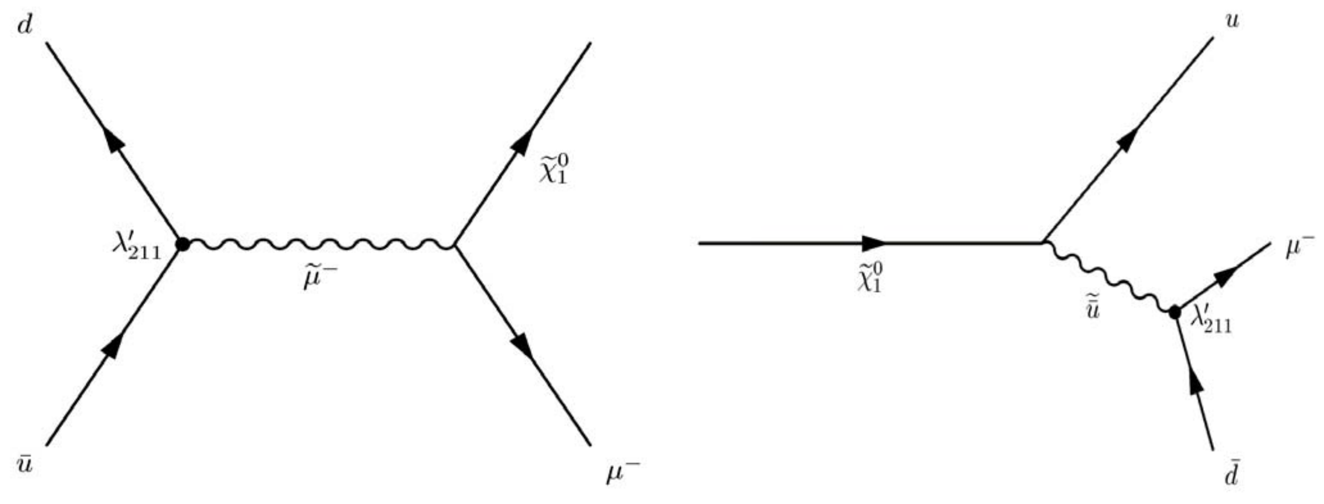

Figure 14: The resonant production of $\tilde{\mu}$, via RPV coupling λ'_{211}, in $p\bar{p}$ collision, and its subsequent decays.

When all the selection cuts are applied, reasonable agreement between the SM expectation and the number of data events are observed for all the SUSY parameter points explored in this analysis. The dominant SM processes are from $\gamma^*/Z + 2$jets, $W +$ jets, and di-boson productions. These results are then interpreted in the mSUGRA framework for the set of parameters $A_0 = 0$, $\tan\beta = 2$, and $\mu < 0$. The 95% C.L. exclusion region in the plane of λ'_{211} vs the $\tilde{\mu}$ mass, for $M_{\tilde{\chi}^0_1} = 75$ GeV/c^2 is shown in Figure 15. The DØ Run II preliminary results have extended the exclusion region well beyond its Run I limits.

3.3. Search for Resonant Squark Production at HERA

The ep collider HERA is an ideal place to search for new particles that couple to electron/positron and quark. In this section it is assumed that electron refers to both e^+ and e^-, unless it is explicitly stated. In supersymmetry

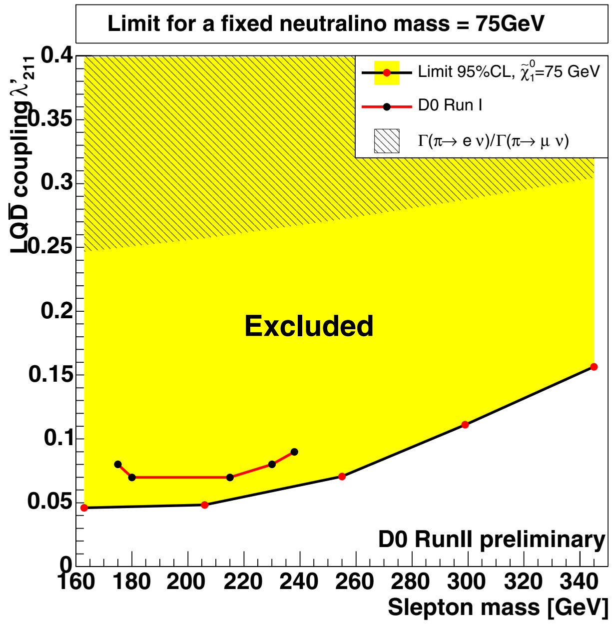

Figure 15: The 95% C.L. exclusion region in the plane of λ'_{211} vs the $\tilde{\mu}$ mass, for $M_{\tilde{\chi}_1^0} = 75$ GeV/c^2

with Rp violation, a squark can couple to an electron and a quark via the Yukawa coupling λ'_{ijk}. Therefore resonant squarks can be produced at HERA through the fusion of the incoming electron and a quark from the incoming proton. In e^+p collision, the squark resonance production is most sensitive to the λ'_{1j1} (j =1,2,3) coupling since the positron has to fuse with a quark of charge $Q = -2/3$ or $Q = -1/3$. At high Bjorken-x, the particle density function for down quark is larger than the anti-up quark. Thus the resonant squark produced will be predominantly up-type squark ($\tilde{u}_L$,$\tilde{c}_L$,$\tilde{t}_L$). In the case of e^-p collision, the squark resonance production will be most sensitive to the λ'_{11k} (k =1,2,3). The electron has to fuse with a quark of charge $Q = +2/3$ or $Q = +1/3$, and the particle density function for up quark is larger than the anti-down quark at high Bjorken-x. Therefore the resonant squark production will be predominantly down-type squark ($\tilde{d}_R$,$\tilde{s}_R$,$\tilde{b}_R$). The diagram for resonant squark production at HERA is shown in Figure 16.

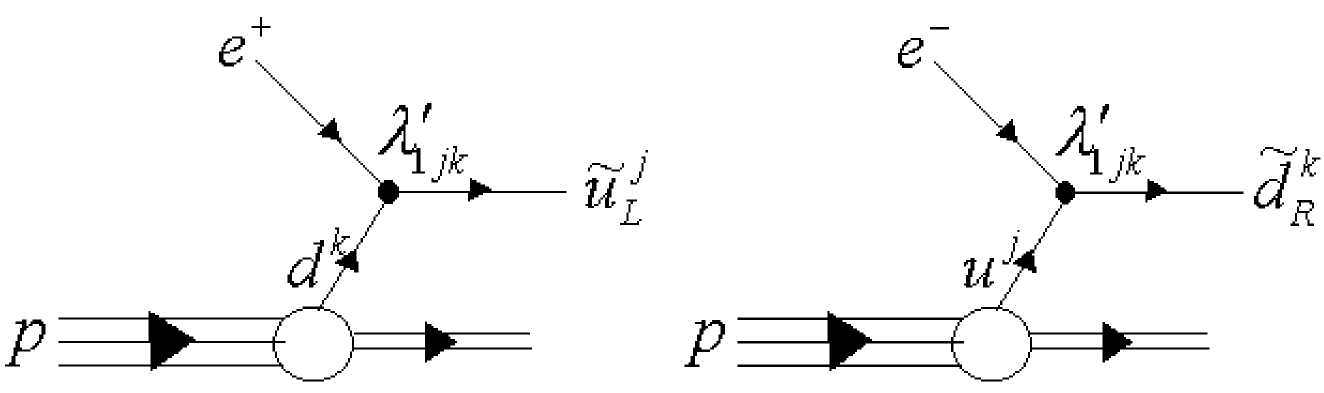

Figure 16: The diagram for resonant squark production at HERA via the RPV λ'_{1jk} coupling. (left) In e^+p collisions. (right) In e^-p collisions.

The H1 experiment has searched for resonant squark production at HERA using data corresponding to integrated luminosity of 64.3 pb^{-1} for e^+p collisions, and 13.5 pb^{-1} for e^-p collisions [16]. The center of mass energy for both

e^+p and e^-p collisions is $\sqrt{s} = 318$ GeV. The search covers many of the Rp violating decay channels of the resonantly produced squark. The squark can undergo a direct Rp violation by decaying directly into eq or νq. In the final state, there is an electron and a jet, or missing energy and a jet. The squark can also undergo a guage decay (conserving Rp) into states involving a neutralino, a chargino, or a gluino. The final state depends on the subsequent gaugino decays. Each decay channel ends with the Rp violating decay of one sparticle, usually the LSP, and the final state will consist of one or two leptons and multi-jets. The diagram for direct Rp violation squark decay, and the gauge decay of squark, are shown in Figure 17. Table III shows the observed number of events in the data and the SM expectation for various decay channels, for both e^+p and e^-p collisions. No excess of events is observed in the data. The search results are interpreted in both MSSM and mSUGRA framework.

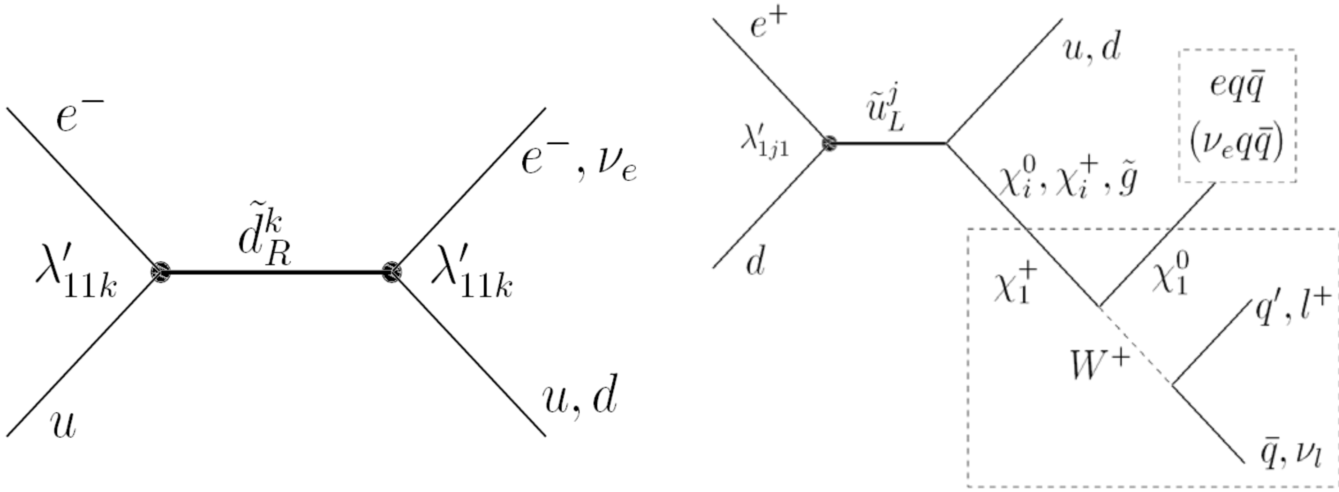

Figure 17: The diagram for (left) direct Rp violation squark decay, and (right) the gauge decay of squark.

Table III: Search for resonant squark production at HERA by the H1 experiment. The observed number of events in the data and the SM expectation for various squark decay channels, for both e^+p and e^-p collisions. The $\tilde{u}_L$-type squark produced in e^+p collisions cannot decay into νq.

	e^+p collisions		e^+p collisions	
Channel	Data	SM expectation	Data	SM expectation
eq	632	628 ± 46	204	192 ± 14
νq			261	269 ± 21
eMJ ("right" charge)	72	67.5 ± 9.5	20	17.9 ± 2.4
eMJ ("wrong" charge)	0	0.20 ± 0.14	0	0.06 ± 0.02
$eeMJ$	0	0.91 ± 0.51	0	0.13 ± 0.03
$e\mu MJ$	0	0.91 ± 0.38	0	0.20 ± 0.04
$e\nu MJ$	0	0.74 ± 0.26	0	0.21 ± 0.07
νMJ	30	24.3 ± 3.6	12	10.1 ± 1.4
$\nu\mu MJ$	0	0.61 ± 0.12	0	0.16 ± 0.03

In the MSSM framework, it is assumed that the gaugino mass terms unify at the GUT scale to a common value of $m_{1/2}$. All the squarks and sleptons are assumed to be degenerate in mass. The slepton mass is set at 90 GeV/c^2. The dependence of the sensitivity on the MSSM parameters is studied by scanning over the SUSY parameters M_2 and μ ($70 < M_2 < 350$ GeV/c^2, $-300 < \mu < 300$ GeV/c^2) for $\tan\beta = 6$. The upper bounds on the couplings λ'_{1j1} and λ'_{11k} are obtained for each point in the (μ,M_2) plane. For $\lambda'_{1j1} = 0.3$ ($\lambda'_{11k} = 0.3$) $\tilde{u}_L$,$\tilde{c}_L$,$\tilde{t}_L$ ($\tilde{d}_R$,$\tilde{s}_R$,$\tilde{b}_R$) squarks with mass below ~ 275 GeV/c^2 (~ 280 GeV/c^2) are excluded at the 95% C.L. . Squarks with mass below ~ 220

GeV/c^2 are also excluded at the 95% C.L. for $\lambda'_{1j1} = 0.03$ ($\lambda'_{11k} = 0.03$). Figure 18 shows the exclusion region for λ'_{1j1} as function of the squark mass.

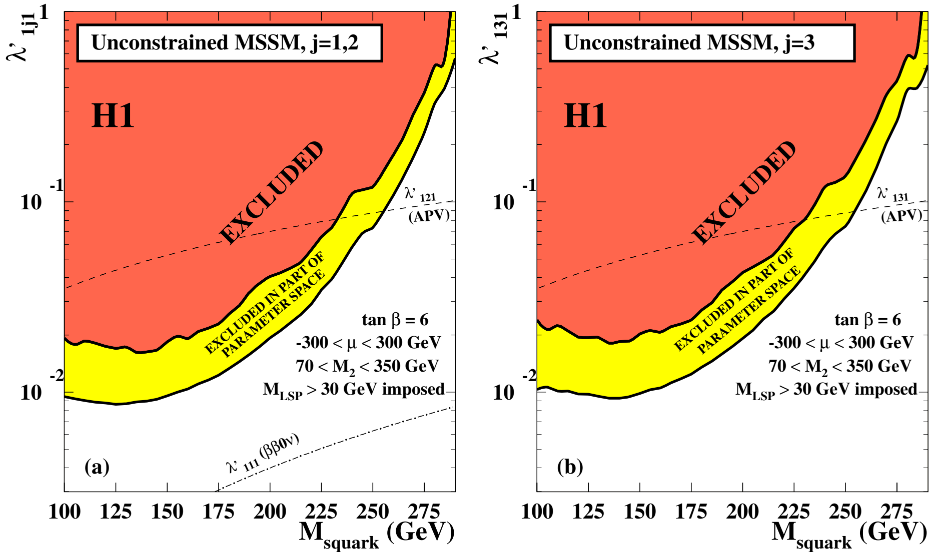

Figure 18: The exclusion region at 95% C.L. on λ'_{1j1} for (a) $j = 1,2$ and (b) $j = 3$ as function of the squark mass from a scan of the MSSM parameter space.

In the mSUGRA framework, to set a constraint on the m_0 and $m_{1/2}$ parameters, the Rp violating couplings λ'_{1j1} and λ'_{11k} are assumed at a fixed value. The values of other mSUGRA parameters ($\tan\beta$, A_0, and the sign of μ) are also fixed. Figure 19 shows the 95% C.L. exclusion region in the (m_0,$m_{1/2}$) plane for $\tan\beta = 6$, and $\lambda'_{1j1} = 0.3$ and $\lambda'_{11k} = 0.3$. For the case of up-type squark production (λ'_{1j1}), the exclusion region for $\tilde{t}_L$ production is larger than for $\tilde{u}_L$ and $\tilde{c}_L$ productions. This is due to the mixing in the stop sector which leads to stop mass smaller than the masses of other squarks. This allows larger values of m_0 and $m_{1/2}$ to be probed. For the case of down-type squark production (λ'_{11k}), the exclusion region from $\tilde{b}_R$ production is similar to $\tilde{d}_R$ and $\tilde{s}_R$ productions. This is because the mixing in the sbottom sector is smaller at $\tan\beta = 6$, than in the stop sector.

4. SUMMARY

The experiments at the Tevatron and HERA colliders have performed searches for supersymmetry. However they have not yet observed any hint of its existence, and thus have set many of the world's best limits on the theory. As the experiments are still collecting data, we will expect more exciting results from the two colliders in the coming years.

Acknowledgments

I would like to thank the staff at the Fermi National Accelerator Laboratory for doing an excellent job in making the possibility of searching for supersymmetry at the Tevatron. I would also like to thank the people at CDF, DØ , H1, and ZEUS for helping me to gather the materials for this talk.

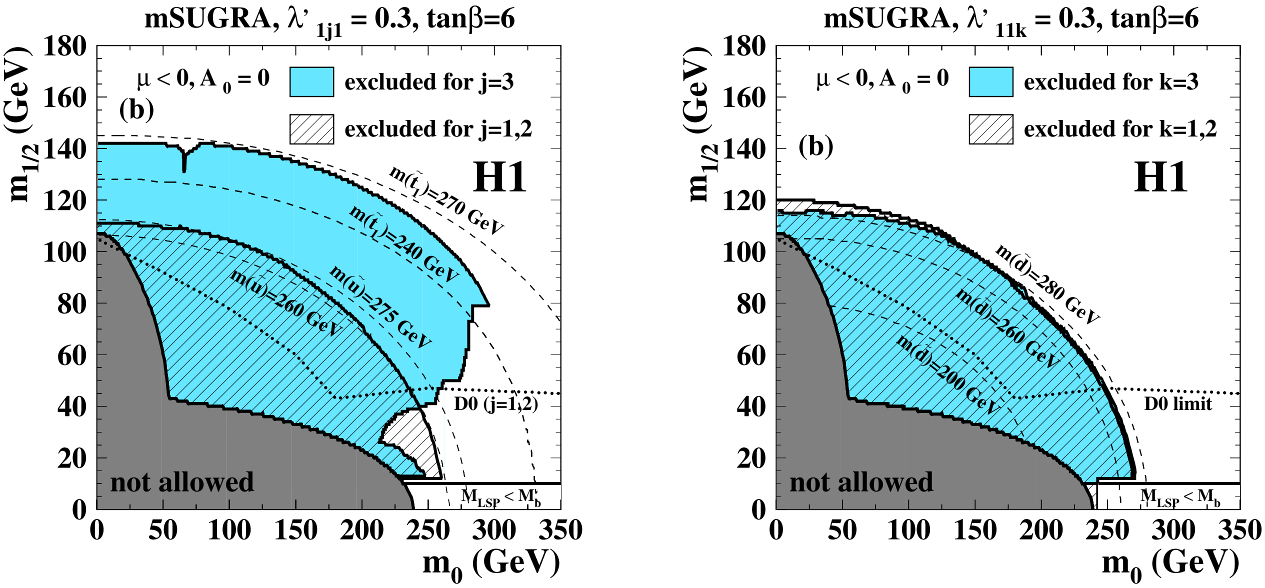

Figure 19: In the mSUGRA framework, the 95% C.L. exclusion region in the (m_0,$m_{1/2}$) plane for $\tan\beta = 6$, and (left) $\lambda'_{1j1} = 0.3$ and (right) $\lambda'_{11k} = 0.3$

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