CDF/PUB/EXOTIC/PUBLIC/9176

A Unified Search for Associated Production of Chargino-Neutralino at CDF using leptons

The CDF Collaboration

URL: http://www-cdf.fnal.gov

August 13, 2008

Abstract

We present a search for the associated production of chargino and neutralino supersymmetric particles using data collected by the CDF II experiment at the Tevatron. We analyze an integrated luminosity of 2.0 fb^{-1}. We analyze events with three charged leptons and momentum imbalance split into five exclusive channels. Overall, we expect a total of 0.9 ± 0.1 background events for trilepton channels, and 5.5 ± 1.1 background events for dilepton+track channels with 2 fb^{-1} of data, expect to observe 4.5 ± 0.4, and 6.9 ± 0.6 signal events for a particular choice of mSUGRA model parameters respectively and we observe 1 events in the trilepton channel and 6 events in the dilepton+track channels.We observe no excess over standard model expectation and set upper limits on the production cross section in the mSUGRA model.

Preliminary results

1 Introduction

Supersymmetry (SUSY) [1] is one of the primary theories for physics beyond the standard model. SUSY proposes a symmetry between fermions and bosons and predicts a 'superpartner' for all standard model particles. The superpartner for a standard model particle differs from it only by a half-unit of spin. SUSY offers solutions to the fine-tuning problem and a possible mechanism for electroweak symmetry breaking (EWSB). It also makes possible for a unification of the gauge couplings at near the Planck scale. An added benefit of SUSY is that it provides an excellent candidate for cold dark matter in certain models. In this analysis we focus on models which give a leptonic signature. One such model is mSUGRA [2], where gravity mediates SUSY breaking from the grand unification theory (GUT) scale to the EWK scale. With R-parity conservation, mSUGRA can be completely characterized by five parameters: a common scalar mass (m_0), a common gaugino mass ($m_{1/2}$), a common trilinear coupling value (A_0), the ratio of the vacuum expectation values of the two Higgs doublets ($\tan(\beta)$), and the sign of the Higgsino mass parameter ($\mathrm{sgn}(\mu)$).

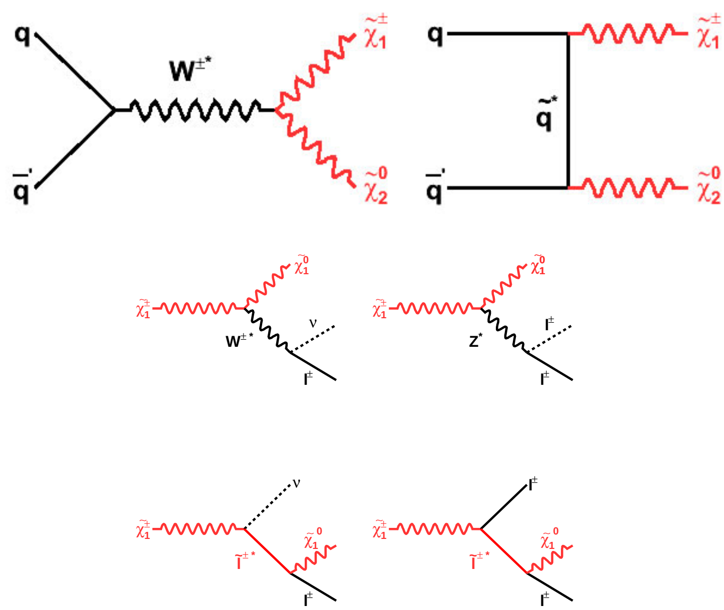

Figure 1: On top we show the s-channel and t-channel production mechanisms for $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$, below we show the decays of the $\tilde{\chi}_1^{\pm}$and $\tilde{\chi}_2^0$via virtual W/Z or virtual sleptons.

One of the most distinctive signatures of SUSY is the associated production of the lightest chargino $\tilde{\chi}_1^{\pm}$ and the second-to-lightest neutralino $\tilde{\chi}_2^0$ and their subsequent decay into three leptons and unobservable particles (neutrinos, and the lightest neutralino $\tilde{\chi}_1^0$). The $\tilde{\chi}_1^{\pm}$ and the $\tilde{\chi}_2^0$ are the mass eigenstates of the superpartners of the electroweak gauge and Higgs bosons. The production and decay of the $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ is shown in Figure 1. The two production mechanisms interfere destructively, with the s-mode through a virtual W exchange being dominant. The decays are through virtual W/Z or through sleptons. The $\widetilde{\chi}_1^0$is the lightest SUSY particle, and if R-parity is conserved, it is stable and so escapes detection. This signature has low standard model backgrounds which are mainly from electroweak processes.

The current world limit on the mass of $\widetilde{\chi}_1^{\pm}(M_{\chi_1^{\pm}})$ is 103.5 GeV/c^2 [3] at the 95% confidence level from LEP direct searches. The most recent DZero tri-lepton search [4] increased that limit to 117 GeV/c^2 in the parameter space where the leptonic branching fractions of $\widetilde{\chi}_2^0$ and $\widetilde{\chi}_1^{\pm}$ are enhanced. A previous CDF search [5] further improved that limit to 129 GeV/c^2 in a scenario comparable to the DZero one. However it should be noted that the model considered by DZero for their result has significant differences from our interpretation in mSUGRA model, and comparisons between the two results need to be done carefully after accounting for model differences. No direct limits on chargino mass in the mSUGRA model have been set so far at the Tevatron, and this analysis sets the first such direct exclusion of chargino mass in mSUGRA.

2 Data and Intial Event Selection

Channels	**Selection**	$(E_T/P_T)_{1,2,3}GeV$
3tight	3 tight leptons or 2 tight leptons + 1 loose electron	15, 5, 5
2tight,1loose	2 tight leptons + 1 loose muon	15, 5, 10
1tight,2loose	1 tight leptons + 2 loose leptons	20, 8, 5(10 if loose muon)
2tight,1Track	2 tight leptons + 1 isolated track	15, 5, 5
1tight,1loose,1Track	1 tight + 1 loose lepton + 1 isolated track	20, 8(10 if loose muon), 5

Table 1: The exclusive analysis channels. A 'tight' selection for leptons is a restrictive selection, for a 'loose' lepton the selection os made a little less restrictive to increase acceptance.

This analysis is carried out in an statistically unbiased way using 2.02 fb^{-1}of integrated luminosity collected by the CDF II detector [6] at the Tevatron between March 2002 and May 2007. The $p\overline{p}$ collision data is at center-of-mass energy of $\sqrt{s} = 1.96$ TeV. The CDF II detector is cylindrical around the beam pipe. The innermost layers are a eight-layer silicon strip detector and a 96-layer drift chamber, both inside a solenoid providing a 1.4T magnetic field. The magnetic field is aligned along the beam axis. These provide measurements of the transverse momentum (p_T) of charged particles. Electromagnetic and hadronic calorimeters surrounding the solenoid measure particle energies. The muon systems are outermost and consist of wire chambers and scintillators.

The events are triggered by either one well-identified central electron(or muon) with $E_T > 18$ GeV ($P_T > 18$ GeV/c) or with two central electrons(muons) with $E_T > 4$ GeV ($P_T > 4$ GeV/c). Henceforth, a lepton refers to e or μ. The selection of leptons is split into two categories : a 'tight' category with restrictive requirements to keep high purity and a 'loose' category with some requirements relaxed to keep high acceptance. The selection of leptons in the two categories is exclusive - leptons are loose only when they do not pass tight requirements. In addition, to be sensitive to the single-prong decay of tau-leptons, we also select isolated tracks [1]. Isolated tracks are also able to catch the electrons and muons which fail the tight and loose requirements. Electrons are required to have a consistent shower shape in the calorimeter and a track pointing to the cluster. The energy deposited in the calorimeter is expected to be consistent with the track momentum. Muons are required to have energy deposits consistent with minimum ionizing particles along with an associated track. All leptons and tracks are required to be isolated from other particles and hadronic activity in the event. The isolation requirement is based on calorimeter deposits alone for some channels and calorimeter deposits and tracks for other channels. Photon conversions and cosmic rays are rejected.

We now describe the five exclusive channels of the analysis. The five channels can be divided broadly into two categories, channels with three leptons and channels with two leptons and a 'track' (charged particle in the tracking system) where lepton= e, μ. The channels with three leptons have very small standard model backgrounds and are 'purer'. The dilepton + track channels are sensitive to single-prong hadronic decays of the τ lepton. The trilepton channels are further divided into three exclusive channels according the the purity of the lepton identification. The dilepton + track channels are divided into two along the same lines. The selection of the five final channels is exclusive. Table 1 shows the selection of the exclusive analysis channels and the E_T(P_T for muons, tracks) requirements on the leptons and track and the nomenclature used to refer to the channels.

3 Standard Model Backgrounds

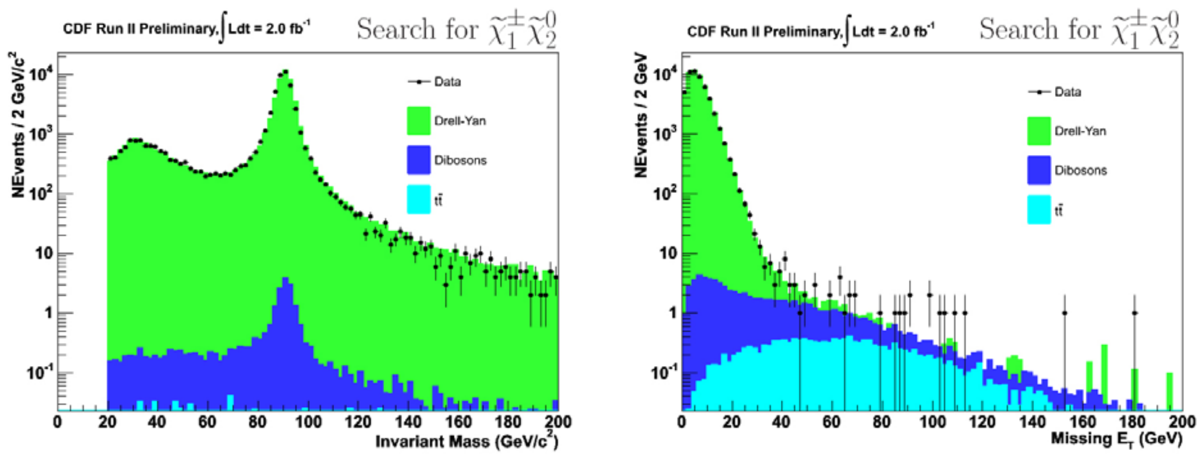

Figure 2: On the left is the invariant mass distribution of two leptons for **dilepton** events with missing E_T < 10 GeV. On the right is the missing E_T distribution for **dilepton** events with invariant mass $76 < M_{\ell\ell} < 106$ GeV/c^2.

The dominant sources of standard model background are the diboson production WZ,ZZ,WW

[1] Track isolation is evaluated based on nearby track activity.

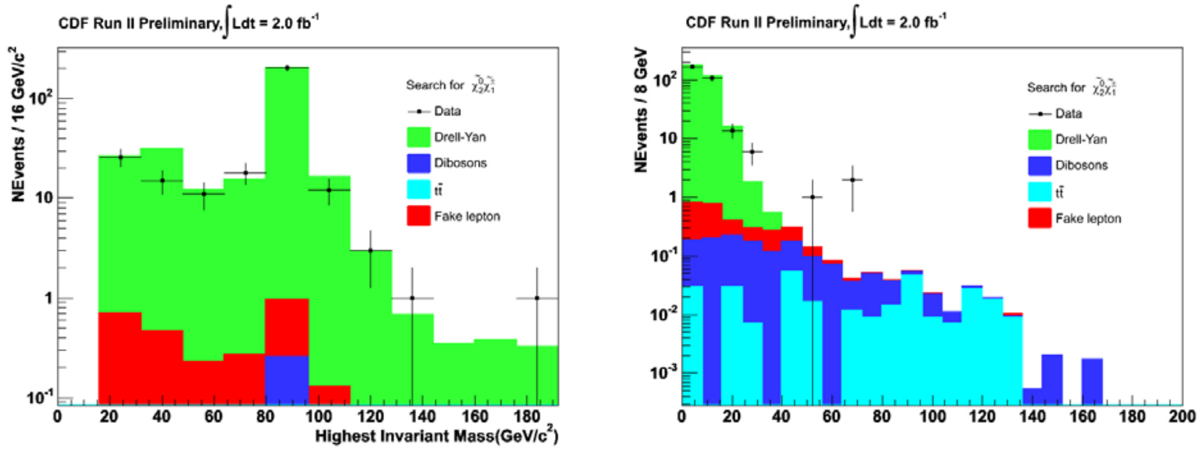

Figure 3: On the left is the highest invariant mass of opposite-charge pairs for **dilepton+track** events with missing $E_T < 10$ GeV. On the right is the missing E_T distribution for **dilepton+track** events with highest invariant mass $76 < M_{\ell\ell} < 106$ GeV$/c^2$.

where Z denotes the production of a Z boson or a virtual photon γ^*, and the Drell-Yan production where the third lepton comes from a bremsstralhlung photon converting ($Z + \gamma$, with $\gamma \to e^+e^-$) or from a misidentified hadron. In case of the dilepton + track channels the track could come from the hadronization of spectator quarks in the collision (underlying event). A smaller contribution to the background comes from the top-pair($t\bar{t}$) production.

Backgrounds are estimated from data and Monte Carlo (MC) event generators. The diboson processes are fairly well understood and we use MC to estimate backgrounds arising from dibosons and $t\bar{t}$ production. To estimate backgrounds from misidentified hadrons, the probability of misidentification is measured in jet data samples and applied to data events with two leptons and a jet. The track backgrounds are estimated by obtaining the rate of getting isolated tracks accompanying Drell-Yan event in $Z \to \ell^+\ell^-$ events in data, and then applying this rate to the MC samples.

4 Control Regions

We test our predictions in a set of control regions for each channel individually. The control regions are tested first at the dilepton level, where we select two leptons in each event. We then select the third lepton(track) and check the control regions. Along with numerical predictions for the control regions, distributions of various kinematic quantities are also checked. Overall there are 47 control regions including 25 exclusive control regions along with a couple hundred distributions. We find good agreement in our control regions and feel confident of our predictive ability. Figures 2 and 3 show a few distributions in our control regions.

5 Advanced Cuts

The benchmark mSUGRA point we consider has following parameters:

$$m_0 = 60 \text{ GeV},\ m_{1/2} = 190 \text{ GeV},\ \tan(\beta) = 3,\ A_0 = 0, \text{ and } \mu > 0 \tag{1}$$

The corresponding masses of interest are: $M_{\tilde{\chi}_1^\pm} = 119.6$ GeV, $M_{\tilde{\chi}_2^0} = 122$ GeV, and $M_{\tilde{\chi}_1^0} = 67$ GeV. and the corresponding $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production cross section is 0.5 pb [7].

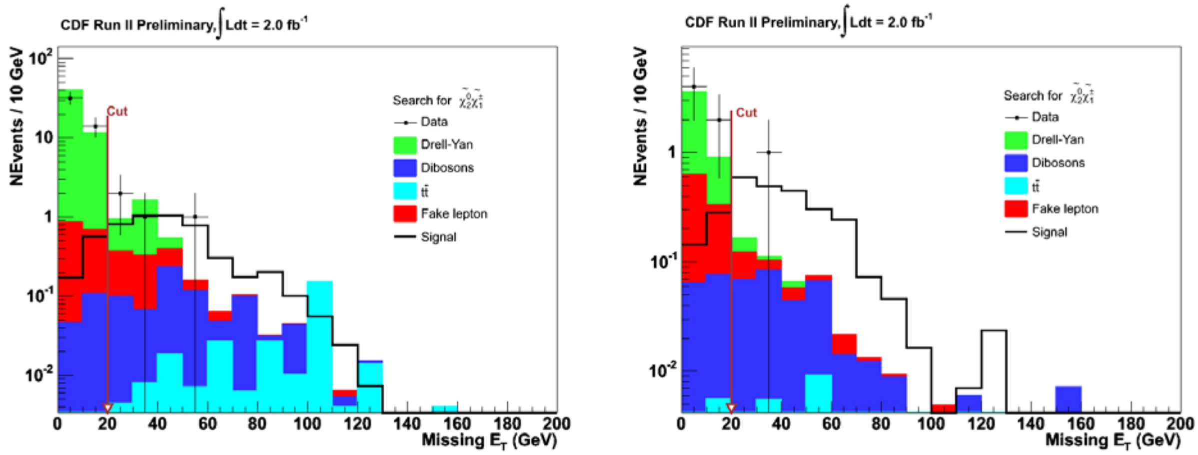

Figure 4: On the left is the $\not\!\!E_T$distribution for the dilepton+track channel (**2tight,1Track**) after all selections, on the right is the same for the trilepton channel (**3tight**). We keep events with $\not\!\!E_T$> 20 GeV.

Since the three leptons in the signal event cannot be of the same sign, we require

$$|\Sigma Q_i| = 1 \tag{2}$$

where Q_i is the charge of the i^{th} lepton(track). This gives us two opposite sign pairs of leptons(lepton-track). We also require that the larger of the two masses formed by opposite-charge lepton(lepton-track) pairs be above 20 GeV/c^2 and the smaller be above 13 GeV/c^2 to remove J/Ψ, and Υ events. To further reduce backgrounds, we apply the following selections:

- $\not\!\!E_T > 20$ GeV. Signal events tend to have higher missing transverse energy ($\not\!\!E_T$) than Drell-Yan background due to the undetected neutrals. We require that events have $\not\!\!E_T > 20$ GeV.
- $\Delta\phi_{\ell_1\ell_2} < 2.9(2.8)$ radians. Leptons in the SUSY event are not as back-to-back as in the Drell-Yan events. We require that neither of the opposite-charge pairs of leptons(lepton-track) has azimuthal separation($\Delta\phi$) $> 2.9(2.8)$ radians for trilepton(dilepton+track) channels.
- NJets ≤ 1, $E_T^{jet} < 80$ GeV. Our SUSY signature comes with no associated hadronic activity(jets), and hence any jets in our final state are expected to be from underlying event. We require that there be at most one jet in the event, and its E_T be less than 80 GeV. Jets

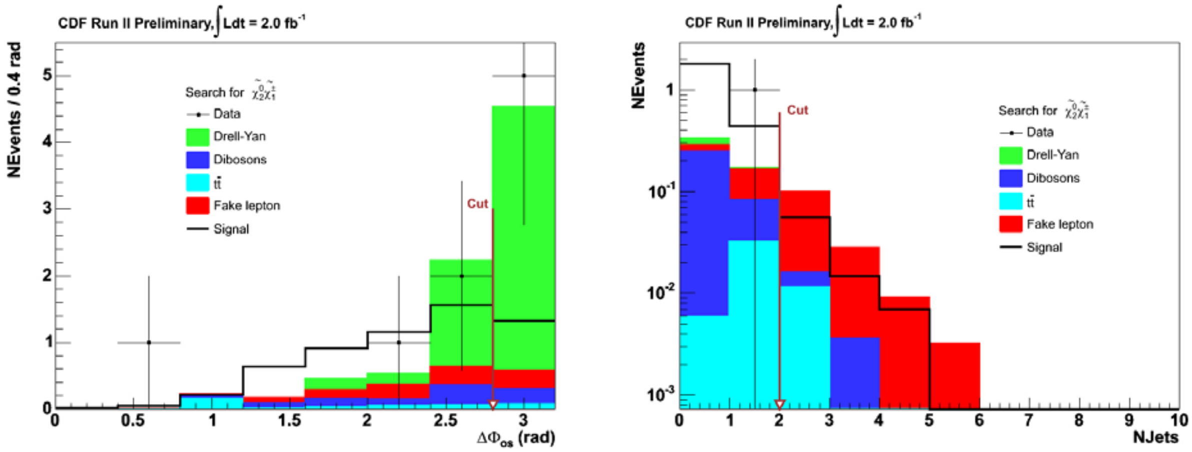

Figure 5: On the left is the $\Delta\phi$ distribution for the dilepton+track channel (**2tight,1Track**) after all selections, we keep events with $\Delta\phi < 2.9$ rad. On the right is the number of jets distribution for the trilepton channel (**3tight**), we keep events with one or zero jets.

from $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \longrightarrow 3l$ process are mostly from initial state radiation (ISR) which contributes little compared to $t\bar{t}$ events.

- $M_{os} < 76$ or $M_{os} > 106$ GeV to reject Z events for both opposite-charge pair masses.

Figure 4 and 5 show the distributions for some of these selections after all other selections have been made.

Channel/Source	ID (%)	Trig (%)	JES (%)	X-sec (%)	PDF (%)	ISR/FSR (%)	Conv (%)	ITR(nom) (%)	ITR(alt) (%)	Fake (%)
3tight	2.3	0.3	1.5	5.0	1.4	2.3	2.2	-	-	12.2
2tight,1loose	2.5	0.3	1.7	5.9	1.6	2.5	2.1	-	-	8
1tight,2loose	2.2	0.3	3.5	5.0	1.3	2.2	1.8	-	-	10.7
2tight,1Track	1.8	0.2	3.9	2.3	1.5	1.8	-	5.8	6.0	11.6
1tight,1loose,1Track	1.8	0.2	5.2	2.4	1.5	1.8	-	8.6	10.5	9.0
Signal	4	0.5	0.5	10	2	4	-	-	-	-

Table 2: The systematic errors for the different channels broken down by source in percentage. A universal 6% uncertainty on the luminosity is not included in this table.

6 Systematic Uncertainties

The systematic uncertainties are shown in Table 2 broken down by various sources. The uncertainties arise from lepton identification(ID), trigger efficiencies(Trig), jet energy scale(JES), process cross sections(X-sec), parton distribution functions(PDF), initial and final state radiation(ISR/FSR), removal of photon conversions(Conv), isolated track rate measurements (ITR) for dilepton+track channels with two parametrizations, a nominal(nom) one and an alternate(nom) one. The Fake uncertainty is largest, and its source is the misidentification of hadrons as leptons. In addition to these, there is also a universal 6% uncertainty on the luminosity.

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Channel	Signal	Background	Observed
3tight	2.25 ± 0.13(stat) ± 0.29(syst)	0.49 ± 0.04(stat) ± 0.08(syst)	1
2tight,1loose	1.61 ± 0.11(stat) ± 0.21(syst)	0.25 ± 0.03(stat) ± 0.03(syst)	0
1tight,2loose	0.68 ± 0.07(stat) ± 0.09(syst)	0.14 ± 0.02(stat) ± 0.02(syst)	0
Total Trilepton	4.5 ± 0.2(stat) ± 0.6(syst)	0.88 ± 0.05(stat) ± 0.13(syst)	1
2tight,1Track	4.44 ± 0.19(stat) ± 0.58(syst)	3.22 ± 0.48(stat) ± 0.53(syst)	4
1tight,1loose,1Track	2.42 ± 0.14(stat) ± 0.32(syst)	2.28 ± 0.47(stat) ± 0.42(syst)	2
Total Dilepton+Track	6.9 ± 0.2(stat) ± 0.9(syst)	5.5 ± 0.7(stat) ± 0.9(syst)	6

Table 3: Number of expected signal and background events and number of observed events in 2 fb^{-1}. Uncertainties are statistical(stat) and full systematics(syst). The signal is for the benchmark point described in section 5.

7 Results

Using the selections described in Section 5, the expected number of signal and background events are shown in Table 3. The signal expectation is for the benchmark mSUGRA point. We expect for the trilepton channels 0.88±0.14 events from SM processes and we observe 1 event. For dilepton+track channels we expect 5.5±1.1 events from SM processes and we observe 6 events. (The signal for an alternate mSUGRA point is shown in Table 4.)

Our observation is consistent with standard model predictions and we see no evidence of chargino-neutralino production. This allows us to set limits on the cross section times the branching ratio ($\sigma\times$BR) of $p\bar{p} \rightarrow \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow 3l$.

The σ is a smooth function of the mass of the $\tilde{\chi}_1^{\pm}$(or $\tilde{\chi}_2^0$), and thus depends very smoothly on $m_{1/2}$. The branching ratio to three leptons, on the other hand, has many interesting features. Figure 6 shows the BR[3l] in the $m_0 - m_{1/2}$ plane with other mSUGRA parameters fixed as follows

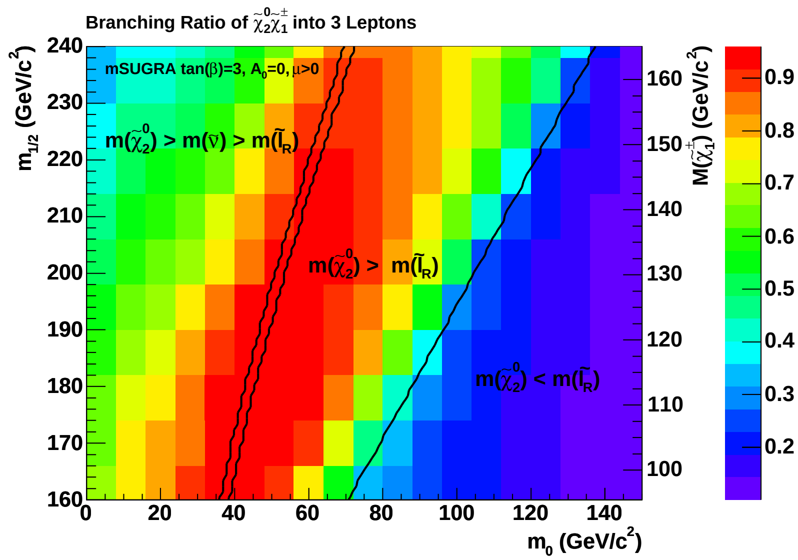

Figure 6: The figure shows the branching ratio to trileptons, BR($\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to$3l) in the $m_0 - m_{1/2}$ plane. The other mSUGRA parameters are kept constant at tan(β)=3, A_0=0, μ >0. The bin size is 10 GeV/c^2 $\times$ 10 GeV/c^2, although in certain places a finer grid is obtained.

: tan(β)=3, $A_0 = 0$, $\mu > 0$. Before describing the features of this plot, it is worthwhile to refresh the decays of the $\tilde{\chi}_1^{\pm}$and $\tilde{\chi}_2^0$. The decays proceed via three-body or successive two-body decays. The three-body decays give the final trilepton state in the following way :
$\tilde{\chi}_1^{\pm} \to l^{\pm}\nu\tilde{\chi}_1^0$, and
$\tilde{\chi}_2^0 \to l^{\pm}l^{\mp}\tilde{\chi}_1^0$ where an intermediate virtual $W^{\pm}$ or Z boson or a virtual slepton is implied.
The two-body decays can proceed via intermediate slepton states as follows :
$\tilde{\chi}_1^{\pm} \to \tilde{l}^{\pm}\ \nu$
$\tilde{\chi}_2^0 \to \tilde{l}^{\pm}l^{\mp}$
where in each case the slepton decays to a lepton and the LSP, $\tilde{l} \to l\tilde{\chi}_1^0$ or via real $W^{\pm}$ or Z decays as follows :
$\tilde{\chi}_1^{\pm} \to W^{\pm}\tilde{\chi}_1^0$, $W^{\pm} \to l^{\pm}\nu$
$\tilde{\chi}_2^0 \to Z\tilde{\chi}_2^0$, $Z \to l^{\pm}l^{\mp}$. The two-body decay branching ratios are thus sensitive to the mass of the sleptons. Let us now examine the various regions of Figure 6.

- Region $\mathbf{m}(\tilde{\chi}_2^0)<\mathbf{m}(\tilde{l}_R)$: This is the region where mass of the sleptons is higher than mass of the $\tilde{\chi}_1^{\pm}$. The decays of the $\tilde{\chi}_1^{\pm}$ and the $\tilde{\chi}_2^0$ proceed through a virtual or real $W^{\pm}$ or Z boson or virtual sleptons, and the branching ratio to the different flavors of leptons (e,μ,τ) are roughly equal.

- Region $\mathbf{m}(\tilde{\chi}_2^0)>\mathbf{m}(\tilde{l}_R)$: This is the region where mass of the right-handed sleptons ($\tilde{e}_R$, $\tilde{\mu}_R$, and the $\tilde{\tau}_1$) is now below mass of the $\tilde{\chi}_1^{\pm}$and $\tilde{\chi}_2^0$. The two-body decays through sleptons enhance the overall branching ratio to leptons. The decays of the $\tilde{\chi}_2^0$ to the three flavors of

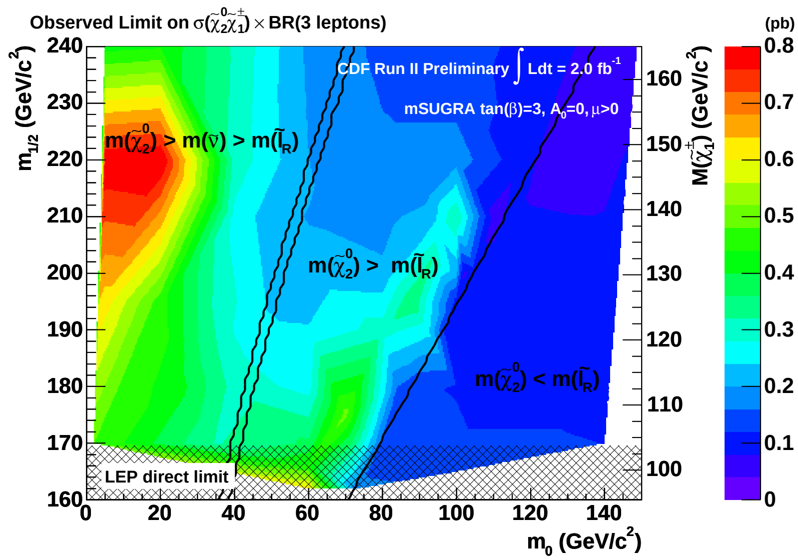

Figure 7: The figure shows the $\sigma \times$BR limits obtained from our result in the plane defined by m_0 and $m_{1/2}$. The regions are described in the text.

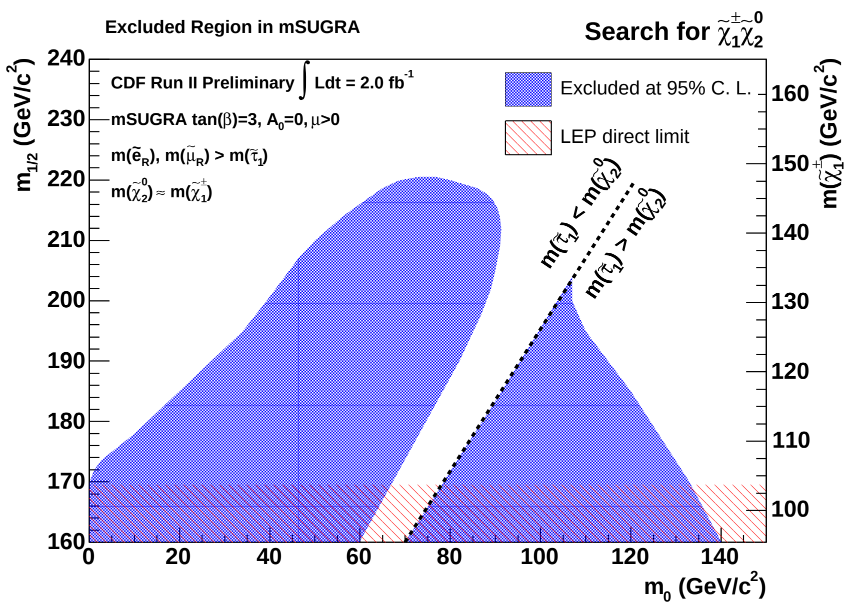

Figure 8: Figure shows exclusion region from this analysis in the $m_0 - m_{1/2}$ plane, with other mSUGRA parameters fixed as described. The LEP direct limit on chargino mass is also shown, along with lines representing significant mass relations. See text for more details.

sleptons are roughly similar, but the $\widetilde{\chi}_1^{\pm}$ decays preferentially to $\tilde{\tau}$'s.

- Region $\mathbf{m(\widetilde{\chi}_2^0)>m(\tilde{\nu})>m(\tilde{l}_R)}$: In this region, the mass of the sneutrinos has also dropped below that of $\widetilde{\chi}_1^{\pm}$. The $\widetilde{\chi}_2^0$ can now also decay as follow $\widetilde{\chi}_2^0 \rightarrow \tilde{\nu}\nu$ which does not contribute to the trilepton signal.

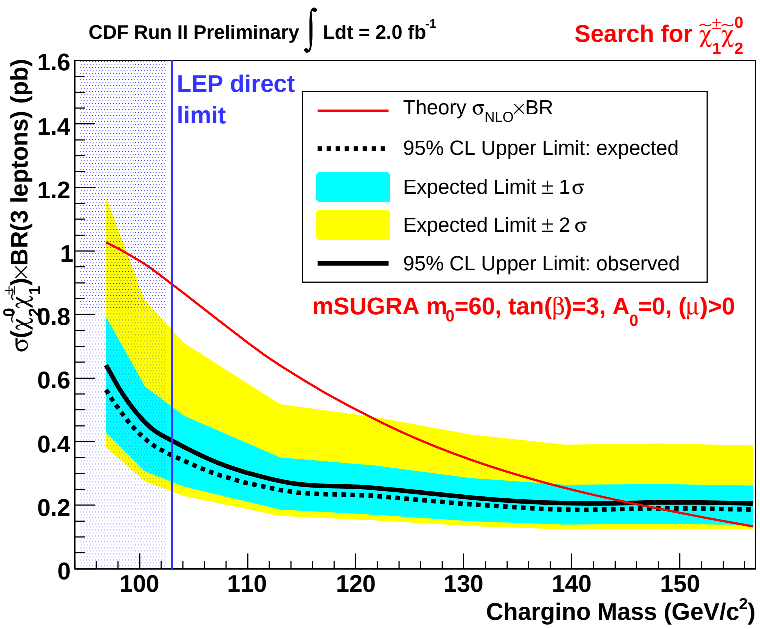

Figure 9: We show the expected and observed limits for $m_0 = 60$ GeV/c^2. The red curve shows the theory cross-section×branching ratio. The black dashed curve shows the expected limit from this analysis (1 σ error in cyan, 2 σ error in yellow). The black solid curve shows the observed limit. We exclude chargino masses below 145.4 GeV/c^2 in this specific scenario.

Figure 7 show the experimentally measured limits. By comparing the experimental limits to the theory expected cross-section × branching ratio, we can define an exclusion region in the $m_0 - m_{1/2}$ plane. We show the exclusion region in Figure 8 where there are two 'lobes' of exclusion. The right lobe (in region m($\widetilde{\chi}_2^0$)<m($\tilde{l}_R$) from Figure 6) is in the region dominated by 3-body decays of $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0$. The left lobe (in the other two regions from Figure 6) is in the region dominated by 2-body decays. The line representing equal masses of $\widetilde{\chi}_1^{\pm}$(or $\widetilde{\chi}_2^0$) and sleptons is also shown. As we move closer to this line from right to left, the sleptons get closer to the $\widetilde{\chi}_2^0$ in mass. The 2-body decay of the $\widetilde{\chi}_2^0$ ($\widetilde{\chi}_2^0 \rightarrow \tilde{l}^{\pm} l^{\mp}$) leads to a soft lepton. This causes the acceptance of the analysis to worsen and thus this region cannot be presently excluded.

For two values of m_0, 60 and 100 GeV/c^2, we show the $\sigma\times$BR limits in Figures 9 and 10. For $m_0 = 60$ GeV/c^2, we exclude chargino masses below 145.4 GeV/c^2, and for $m_0 = 100$ GeV/c^2, we exclude chargino masses below 127.0 GeV/c^2. In Figure 10, at chargino mass of ≈127 Gev/c^2 we cross into the region where slepton is lighter than the chargino. The neutralino decay via the

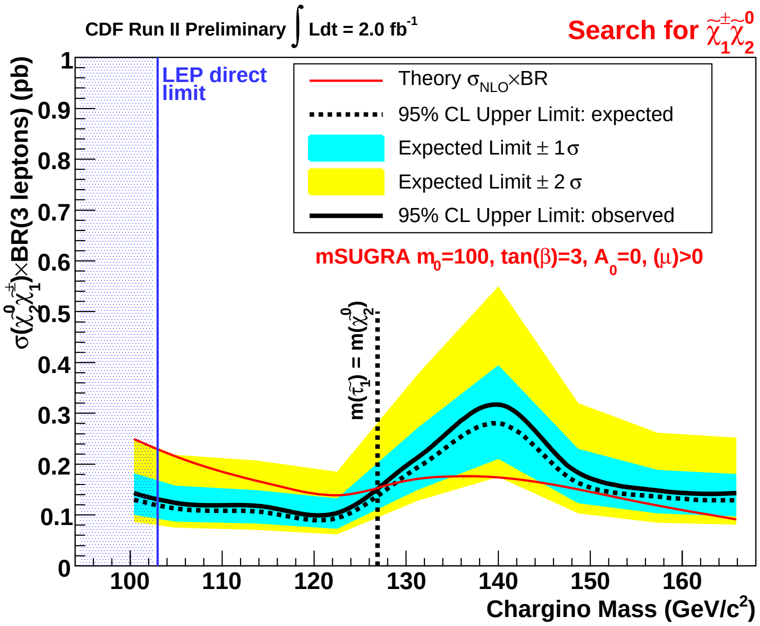

Figure 10: We show the expected and observed limits for $m_0 = 100$ GeV$/c^2$. The red curve shows the theory cross-section×branching ratio. The black dashed curve shows the expected limit from this analysis (1 σ error in cyan, 2 σ error in yellow). The black solid curve shows the observed limit. We exclude chargino masses below 127.0 GeV$/c^2$ in this specific scenario.

sleptons ($\tilde{\chi}_2^0 \rightarrow \tilde{l}^{\pm} l^{\mp}$) gives a soft lepton below the thresholds of our analysis. The acceptance, and thus the limits worsen. The improve once again after the lepton moves over our threshold.

8 Acknowledgments

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium fuer Bildung und Forschung, Germany; the Korean Science and Engineering Foundation and the Korean Research Foundation; the Particle Physics and Astronomy Research Council and the Royal Society, UK; the Russian Foundation for Basic Research; the Comision Interministerial de Ciencia y Tecnologia, Spain; and in part by the European Community's Human Potential Programme under contract HPRN-CT-20002, Probe for New Physics.

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Channel	Signal	Background	Observed
3tight	2.34 ± 0.13(stat) ± 0.27(syst)	0.49 ± 0.04(stat) ± 0.08(syst)	1
2tight,1loose	1.66 ± 0.09(stat) ± 0.20(syst)	0.25 ± 0.03(stat) ± 0.03(syst)	0
1tight,2loose	0.67 ± 0.04(stat) ± 0.08(syst)	0.14 ± 0.02(stat) ± 0.02(syst)	0
Total Trilepton	4.7 ± 0.2(stat) ± 0.6(syst)	0.88 ± 0.05(stat) ± 0.13(syst)	1
2tight,1Track	2.17 ± 0.12(stat) ± 0.25(syst)	3.22 ± 0.48(stat) ± 0.53(syst)	4
1tight,1loose,1Track	1.24 ± 0.07(stat) ± 0.14(syst)	2.28 ± 0.47(stat) ± 0.42(syst)	2
Total Dilepton+Track	3.4 ± 0.1(stat) ± 0.4(syst)	5.5 ± 0.7(stat) ± 0.9(syst)	6

Table 4: Number of expected signal and background events and number of observed events in 2 fb^{-1}. Uncertainties are statistical(stat) and full systematics(syst). The signal is for the mSUGRA point with these parameters : $m_0 = 100$ GeV, $m_{1/2} = 180$ GeV, $\tan(\beta) = 3$, $A_0 = 0$, and $\mu > 0$.

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[7] We use Isajet v7.51 input to Pythia to generate signal Monte-Carlo samples. Isajet is expected to better estimate the mass spectrum of supersymmetric particles than Pythia, however cascade decays of particles are better estimated in Pythia. We use PROSPINO 2.0 to obtain signal cross section, we use Isajet v7.75 to feed the susy mass spectrum for PROSPINO.