CHARGED HIGGS AND SUSY SEARCHES AT CDF

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We present recent results of supersymmetric (SUSY) particle searches at the Collider Detector at Fermilab (CDF). These include searches for squarks, gluinos, charginos, and neutralinos using the $\not{E}_T$-multijet, like-sign dilepton, and trilepton SUSY signatures. Results from a charged Higgs search using the hadronic decays of the tau lepton are also presented.

1 Introduction

Supersymmetric (SUSY) models add a new symmetry to the Standard Model (SM) wherein each fermion has a supersymmetric bosonic partner and vice versa. It contains many desirable features; for example, it

- solves naturalness/fine-tuning problem of the SM,[1]
- preserves agreement with the SM, and
- provides a cold dark matter candidate.

However, the price for these desirable features is a large expansion in the number of free parameters in the model.

A series of assumptions reduces the number of free parameter to a manageable number. We use the minimal supersymmetric extension to the Standard Model (MSSM) containing two Higgs doublets.[2] After electroweak symmetry breaking, there are five Higgs bosons—h°, H°, A°, and $H^\pm$. Assuming absolute conservation of R-parity implies that all SUSY particles must be produced in pairs and that the lightest SUSY particle (LSP) is absolutely stable. The LSP is usually assumed to be the lightest neutral SUSY particle.

Finally, we demand that the theory be consistent with grand unification and supergravity (SUGRA) constraints.[3] These assumptions leave only five free parameters in the model—m_0, $m_{1/2}$, A_t, $\tan\beta$, and $\mathrm{sgn}(\mu)$ where m_0 is the common boson mass, $m_{1/2}$ is the common fermion mass, A_t is the trilinear coupling term, $\tan\beta$ is the ratio of the vacuum expectation values of the two

Higgs doublets, and μ is the Higgs mass parameter. Instead of m_0 and $m_{1/2}$, we use $M_{\widetilde{q}}$ and $M_{\widetilde{g}}$ where $M_{\widetilde{q}}$ is the common mass of squarks (except the third generation) and $M_{\widetilde{g}}$ is the common mass of the gluinos. In this case, both the sign and value of μ are important.

2 Multiple Jet Plus Missing E_T Search

Because of R-parity conservation all SUSY decay chains must contain at least two of the lightest supersymmetric particles. These LSPs are neutral and weakly-interacting; thus, the CDF detector does not directly detect them but identifies them through missing transverse momentum ($\not\!\!E_T$).[2] Conceptually, the simplest search is to look for an excess of events with a large missing transverse momentum. This *inclusive* measurement has a large production cross-section (compared to any individual channel) but also has a large background from Standard Model processes and from detector mismeasurement of $\not\!\!E_T$.

In particular, this search looks for squark and gluino production from $p\bar{p}$ collisions at the Tevatron using 19 pb^{-1} of data. The collisions produce

$$p\bar{p} \rightarrow \widetilde{q}\,\widetilde{q},\ \widetilde{q}\,\widetilde{g},\ \widetilde{g}\,\widetilde{g}$$

where for $M_{\widetilde{q}} > M_{\widetilde{g}}$,

$$\widetilde{q} \rightarrow q\widetilde{g} \text{ and } \widetilde{g} \rightarrow q\bar{q}\widetilde{\chi}_1^0$$

and for $M_{\widetilde{q}} < M_{\widetilde{g}}$,

$$\widetilde{g} \rightarrow \bar{q}\widetilde{q} \text{ and } \widetilde{q} \rightarrow q\widetilde{\chi}_1^0$$

where $\widetilde{\chi}_1^0$ is the LSP. If one of the charginos is lighter than the squarks or gluinos, then the kinematically allowed cascade decays tend to produce more jets and less $\not\!\!E_T$ making this search less sensitive. (The dilepton search described later specifically addresses these cascade decays.)

The analysis identifies events with large $\not\!\!E_T$ and 3 (4) or more jets. In particular, the analysis requires events with:

- $\not\!\!E_T > 60$ GeV,
- $S \equiv \not\!\!E_T/\sqrt{\sum E_T} > 2.2$ (GeV)$^{1/2}$,
- $N_{jet} \geq 3$ or 4 ($E_T > 15$ GeV),
- $\Delta\phi(\not\!\!E_T,\text{jet1}) < 160^\circ$, and
- no identified electrons or muons.

An additional series of "clean-up" cuts removes events from bad runs, cosmic rays, main-ring losses, etc. After all cuts, 23 events remain in the 3 or more jets sample and 6 events remain in the 4 or more jets sample.

In the 3 or more jets sample, $35^{+11}_{-9}\,(stat)\,^{+17}_{-9}\,(sys)$ background events are expected. The largest contributions are from $W \rightarrow \tau\nu$+jet(s) production where the tau has decayed hadronically and from multijet QCD events in which one or more of the jets is mismeasured producing a large, spurious $\not\!\!E_T$. For the 4 or more jet sample, $9^{+4}_{-3} \pm 3$ background events are expected. The primary components are $t\bar{t}$ production and multijet QCD events. In both samples the number of observed events is consistent with the background estimation.

Signal events were simulated using Isajet 7.06 at leading-order. A simple Monte Carlo was used to determine the number of expected signal events necessary to exclude a model at the 95% C.L. This Monte Carlo properly convoluted the errors on the signal and background estimates into the calculation. Models which produce more than 26.7 or 9.4 expected events in the 3 or more jets or 4 or more jets samples, respectively, are excluded. The excluded region in the $M_{\widetilde{q}}$ vs. $M_{\widetilde{g}}$ plane is shown in Fig. 1. Below the diagonal the 3 or more jet analysis is more sensitive; above and on the diagonal the 4 or more jet analysis is more sensitive. Note that below the diagonal, the SUGRA constraints are non-physical. In this region, the slepton masses have been set to 350 GeV/c^2. This analysis excludes $M_{\widetilde{g}} < 169$ GeV/c^2 independent of $M_{\widetilde{q}}$ and $M_{\widetilde{q},\widetilde{g}} < 213$ GeV/c^2 for $M_{\widetilde{q}} = M_{\widetilde{g}}$.

Fig. 1 shows the gluino mass limit as a function of μ for large values of $M_{\widetilde{q}}$. The gluino mass limit is rather insensitive to both μ and $\tan\beta$. Notice that LEP is most sensitive to small $|\mu|$ while CDF is sensitive to large $|\mu|$.

3 Leptonic SUSY Signatures

While the $\not\!\!E_T$ search benefits from a large production cross-section, it suffers from large backgrounds. To avoid backgrounds, we additionally search for leptonic SUSY channels with little background from Standard Model processes. Two, in particular, are a same-sign dilepton signature and a trilepton signature.[5] (Leptons for these analyses are electrons or muons.)

Both analyses use the same lepton identification cuts. Both require that the primary lepton have an $E_T > 11$ GeV; the other lepton(s) must have $E_T > 5$ GeV. All of the leptons must be isolated in both the calorimeter and in the tracking chambers.

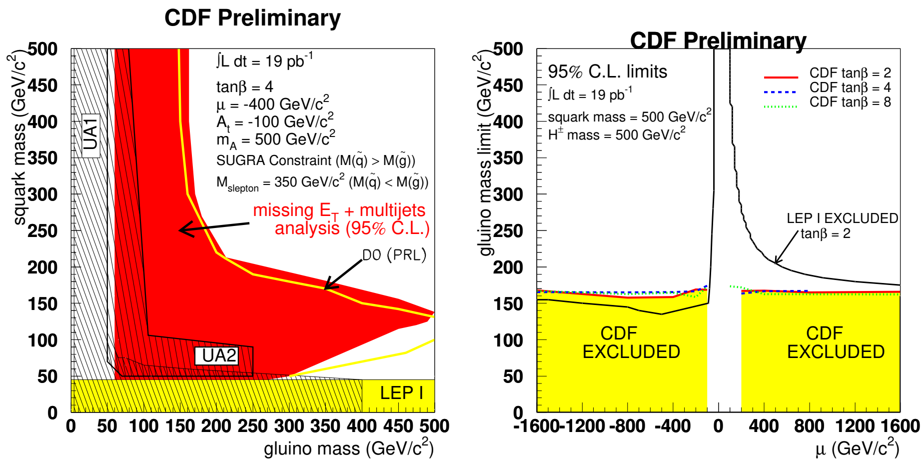

Figure 1: Excluded region (left) from multiple jet plus $\not{E}_T$ analysis.[4] Gluino mass limit as a function of μ and $\tan\beta$.

3.1 Dilepton Search

The dilepton search looks for cascade decays of gluinos. Specifically, a gluino pair is produced in the $p\bar{p}$ collision and each gluino decays $\tilde{g} \to q\bar{q}'\,\tilde{\chi}_1^{\pm}$. The chargino subsequently decays into $\tilde{\chi}_1^{\pm} \to \ell^{\pm}\nu\tilde{\chi}_1^{0}$ resulting in a final state with two leptons with *uncorrelated* sign and four jets.[6]

The analysis requires two *same*-sign leptons and two or more jets in the event all originating from a common vertex. The jets must have a corrected $E_T > 15$ GeV and $|\eta| < 2$. A moderate missing transverse momentum of 25 GeV or more is also required. After all cuts, 2 events remain from a sample of 81 pb^{-1}.

The dominant background contributions are $t\bar{t}$ and Drell-Yan production where the sign of one of the leptons has been mismeasured. Overall, the background contributes $1.3 \pm 0.6\,(stat) \pm 0.4\,(sys)$ events, consistent with the 2 observed events.

Using Poisson statistics and convoluting all of the statistical and systematic errors into the calculation, we exclude any model which produces more than 5.8 events. This calculation uses the next-to-leading order production cross-sections. Fig. 2 shows the exclusion region in the $M_{\tilde{q}}$ vs. $M_{\tilde{g}}$ mass plane. This analysis excludes $M_{\tilde{g}} < 180$ GeV$/c^2$ independent of $M_{\tilde{q}}$ and $M_{\tilde{q},\tilde{g}} <$

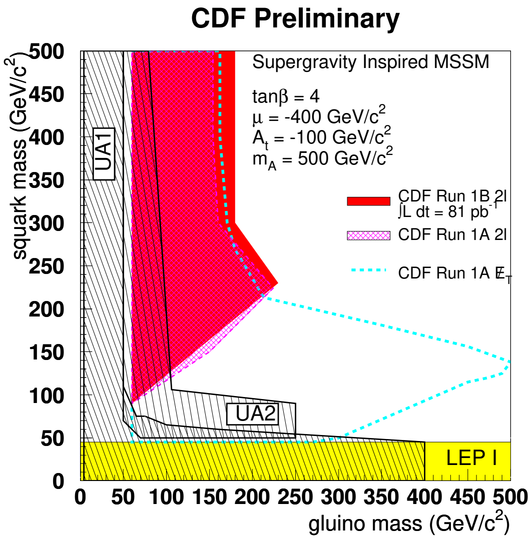

Figure 2: Excluded region from like-sign dilepton analysis.

230 GeV$/c^2$ for $M_{\widetilde{q}} = M_{\widetilde{g}}$.

3.2 Trilepton Search

The trilepton search looks for direct production of chargino, neutralino pairs with subsequent decay of the chargino and neutralino into leptons.[7] That is,

$$p\bar{p} \rightarrow \widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^{\circ} \rightarrow \ell^{\pm}\nu\widetilde{\chi}_1^{\circ}\;\ell^{+}\ell^{-}\widetilde{\chi}_1^{\circ}.$$

Notice that this requires the next-to-lightest neutralino to be produced.

The analysis requires three leptons ($e^+e^-e^{\pm}$, $e^+e^-\mu^{\pm}$, $\mu^+\mu^-e^{\pm}$, $\mu^+\mu^-\mu^{\pm}$) originating from a common vertex. Events with opposite sign leptons consistent with J/ψ (2.9–3.3 GeV$/c^2$), Υ (9-11 GeV$/c^2$), or Z (76–106 GeV$/c^2$) resonances are removed. Each event must also have $\not{E}_T > 15$ GeV. After all of the cuts, no events remain in a data sample of 100 pb^{-1}.

Considering $t\bar{t}$, $b\bar{b}/c\bar{c}$, diboson, and Drell-Yan processes, only 0.4 ± 0.1 background events are expected. Fig. 3 shows the $\sigma \cdot \mathcal{B}$ upper limit at 95% C.L. for $\tan\beta = 2$ and 4. The actual limits are quite competitive with LEP[8] and probe a different region of μ. Note that the LEP limit shown assumes

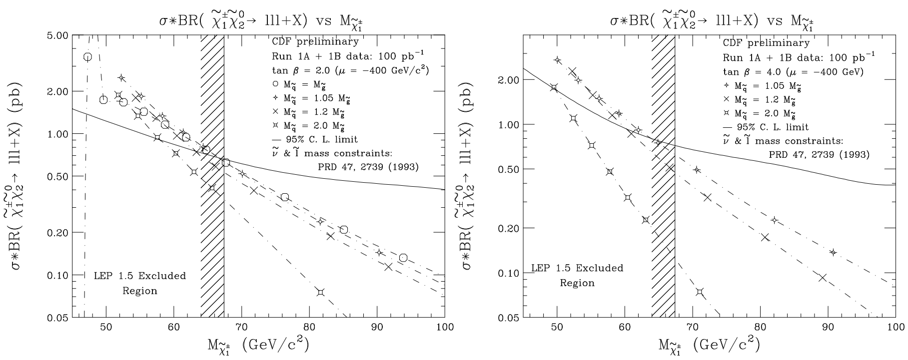

Figure 3: Limit on $\sigma \cdot \mathcal{B}$ for chargino neutralino production into trileptons at the 95% C.L. for $\tan\beta = 2$ (left) and $\tan\beta = 4$ (right).

$M_{\tilde{\nu}} = 100$ GeV/c^2. For smaller values of $M_{\tilde{\nu}}$, the LEP limit degrades because of destructive interference from a t-channel diagram. Fig. 4 shows the small variation of the CDF limit as a function of μ.

4 Charged Higgs Search

Many extensions to the Standard Model contain an expanded Higgs sector. SUSY and E_6 models, for instance, contain two Higgs doublets where one doublet gives mass to the up-type quarks and the other gives mass to the leptons and down-type quarks.[9] After electroweak symmetry breaking, there are five physical Higgs bosons three of which are neutral and two of which are charged.

The ratio $\tan\beta$ controls the dominant decay modes for the charged Higgs and top quark. For large $\tan\beta$, $t \to Hb$ and $H \to \tau\nu$ exclusively. This leads to distinctive events with two tau leptons, two b-jets, and large $\not\!\!E_T$.[10] For smaller values of $\tan\beta$, the top decays are a mixture of $t \to Wb$ and $t \to Hb$. This search requires the topology $\tau jjX + \not\!\!E_T$ where the tau decays hadronically and X can be either an electron, muon, tau, or additional jet. One of the jets in the event must be b-tagged with CDF's silicon vertex detector. The $\not\!\!E_T$ must exceed 60 GeV.

Identification of hadronically decaying taus starts with a jet having $E_T >$ 10 GeV. There must be either one or three charged particles in a 10° cone about the jet axis and no other charged particles above 1 GeV between the 10° cone and a 30° cone. The cluster cannot be consistent with an electron.

After all analysis cuts, 8 events remain in a sample of 88 pb^{-1}. All of these

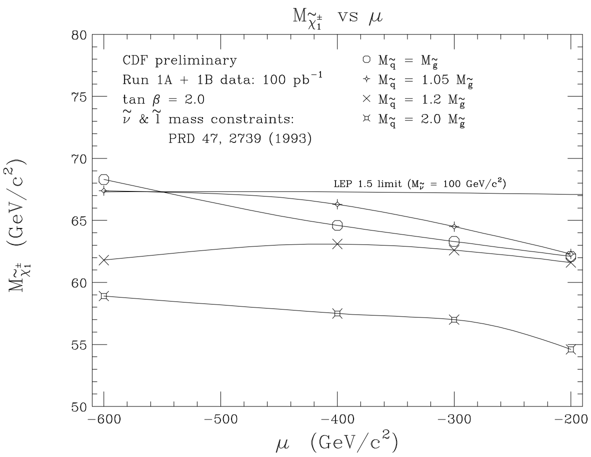

Figure 4: Mass limits from the trilepton search as a function of μ.

events have a $\tau + 3$ jet topology. Jets which have fluctuated to low charged particle multiplicity and have faked a tau lepton comprise the dominant background. We expect 8.5 ± 1.7 background events including small contributions from electroweak processes and diboson production.

Fig. 5 shows the number of expected events vs. $\tan\beta$ for various charged Higgs masses. Also shown is the 95% C.L. upper limit from this search (9.8 events) calculated with Poisson statistics and using the errors on the background and signal estimates. Fig. 6 shows the limit in the M_H vs. $\tan\beta$ plane. For large values of $\tan\beta$ we exclude charged Higgs masses with $M_H <$ 140 GeV$/c^2$.

5 Summary

CDF has searched for evidence squark and gluino production at the Tevatron collider using the multijet plus $\not\!\!E_T$ and the like-sign dilepton channels. We find no evidence for squark and gluino production and set limits on squark and gluino masses. CDF excludes $M_{\widetilde{g}} < 180$ GeV$/c^2$ independent of $M_{\widetilde{q}}$ and $M_{\widetilde{q},\widetilde{g}} < 230$ GeV$/c^2$ for $M_{\widetilde{q}} = M_{\widetilde{g}}$. Similarly, the trilepton search has found no evidence for chargino, neutralino pair production. It excludes charginos with $M \lesssim 60$ GeV$/c^2$. Lastly, CDF excludes a charged Higgs with $M_H <$ 140 GeV$/c^2$ for $\tan\beta \gtrsim 70$.

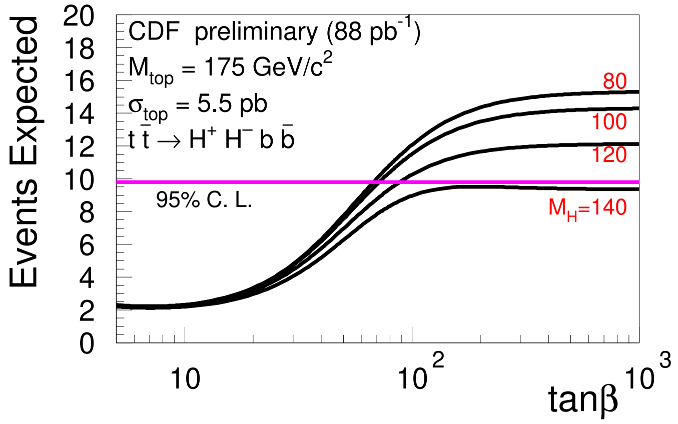

Figure 5: Expected number of charged Higgs events as a function of $\tan\beta$.

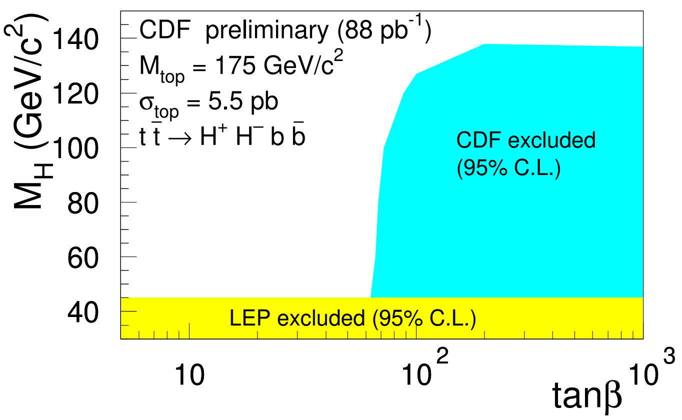

Figure 6: Excluded region in M_H vs. $\tan\beta$ plane.

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