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SUSY Searches at the Tevatron

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Abstract. We present the results of several searches for Supersymmetric (SUSY) particles at the CDF and DØ experiments at the Tevatron at Fermilab. Using data sets as large as 6.3 fb^{-1}, a wide variety of SUSY models are explored. While no excesses are observed in data above the Standard Model background, limits on the production cross section times branching ratio are set. Where appropriate these limits are interpreted within specific SUSY models to calculate mass exclusion limits.

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1. Introduction

Supersymmetry (SUSY) [1] is one of the most popular extensions of the Standard Model (SM). SUSY can lessen the hierarchy problem and allows the unification of the gauge couplings which the SM suffers from. Each SM particle has a corresponding SUSY particle (sparticles) that contributes to the Higgs mass squared with opposite sign relative to the contributions of SM particles. This protects the weak mass scale from divergences. SUSY is a broken symmetry since the sparticles do not have the same mass as their SM partners. If R_p parity is conserved the lightest SUSY particle (LSP) is stable and provides a candidate for cosmological dark matter. This paper discuses several different SUSY models.

2. mSUGRA

The minimal super gravity (mSUGRA) model of SUSY breaking [2] scenario is described by five independent parameters: the unified scalar and gaugino masses m_0 and $m_{1/2}$, the ratio of the vacuum expectation values of the two Higgs doublets, $\tan\beta$, the unified trilinear coupling A_0, and the sign of the Higgs mass parameter μ. These parameters define all the properties (masses, cross sections, etc) of the model. In this model the LSP is weakly interacting and typically identified via missing transverse energy ($\not{E}_T$).

2.1. Gaugino Pair Production in Trilepton Final State

The classical signature for SUSY is $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ decaying to leptons and LSPs. This leads to a final state with 3 leptons and $\not{E}_T$ from a neutrino and LSPs which escape undetected. The advantage of this *trilepton* channel is that three isolated leptons with large $\not{E}_T$has a very low expected background from the Standard Model. The key disadvantage is the leptons are relatively low p_T so identifying them is more difficult. This process also has a low cross section times branching ratio.

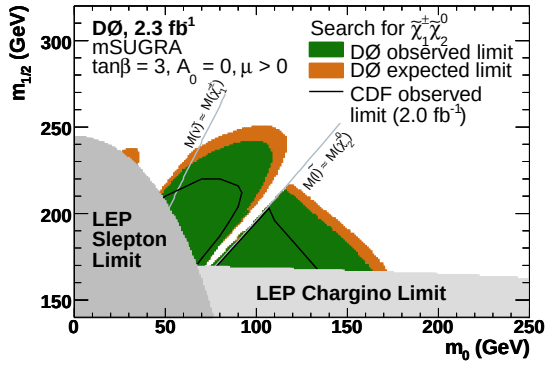

Figure 1. DØ exclusion limit in the $m_{1/2}$-m_0 plane.

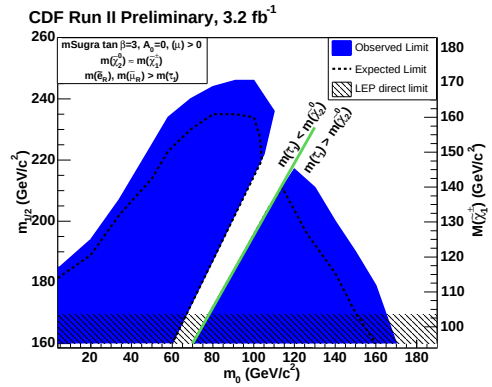

Figure 2. CDF exclusion limit in the $m_{1/2}$-m_0 plane.

In the DØ analysis [3], we define four different channels distinguished by the lepton content of the final state. For channels without τ, one *low-p_T* and one *high-p_T* selection is designed to exploit the different kinematic properties for different mass ranges. Primarily these selections tune the p_T cuts of the leading leptons to maximize the expected sensitivity. The channels which contain τ use only one set of cuts similar to the low-p_T selection. This analysis is performed with data collected until June, 2007, totaling 2.3 fb^{-1}. The analysis using hadronic τ decays is based on 1.0 fb^{-1}.

In the CDF analysis [4], we select events and separate them, based on lepton type (excluding τ), into exclusive samples based on expected purity. This channel independence allows easy statistical combination of the results. We create two control samples to test our background estamates against data. These trilepton events are chosen in a kinematic region where we do not expect any signal. Once we are satisfied with the agreement in the control regions, we apply SUSY specific cuts and look at signal region data to compare against background. This analysis is performed with data collected until 1 July, 2008, totaling 3.2 fb^{-1}.

However, we can turn these null results into exclusions in the mSUGRA model. Assuming a parameter space ($m_0 = 60$ GeV, $\tan\beta = 3$, $A_0 = 0$, and $\mu > 0$) we exclude the chargino ($\tilde{\chi}_1^{\pm}$) of a mass less than 155 GeV/c2 at DØ and less than 164 GeV/c2 at CDF, Figure:1,2.

2.2. Squarks and Guinos in $\not\!\!E_T$+ Jets

Since R-parity is conserved in the mSUGRA model, supersymmetric particles are produced in pairs. At the Tevatron, squarks ($\tilde{q}$) and gluinos ($\tilde{g}$), the superpartners of quarks and gluons, would be produced, if sufficiently light, by the strong interaction. Their decay then leads to SM particles and to the LSP. These decays lead to final states containing jets and $\not\!\!E_T$.

Using 2.1 fb^{-1} and 2.0 fb^{-1} respectively, DØ [5] and CDF [6] perform similar searches looking for excess events in njet plus $\not\!\!E_T$; where n=2,3,4. Both experiments find good agreement between the data and SM expectations. Figure 3 shows this agreement for the CDF analysis. Since there is no excess we can set a limit on the $\tilde{q}(\tilde{g})$ mass, Figure 4. Within the mSUGRA model assuming, $m_{\tilde{q}} \sim m_{\tilde{g}}$, DØ and CDF constrain $m_{\tilde{q}(\tilde{g})} > 390$ GeV.

3. MSSM

Similar to mSUGRA, we can have a generic minimal supersymmetric extension of the SM (MSSM) without the parameter space constraints of mSUGRA. In these MSSM R-parity

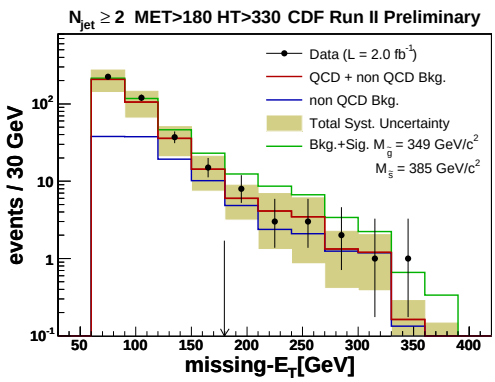

Figure 3. CDF $\not\!\!E_T$ distribution for njet=2 events.

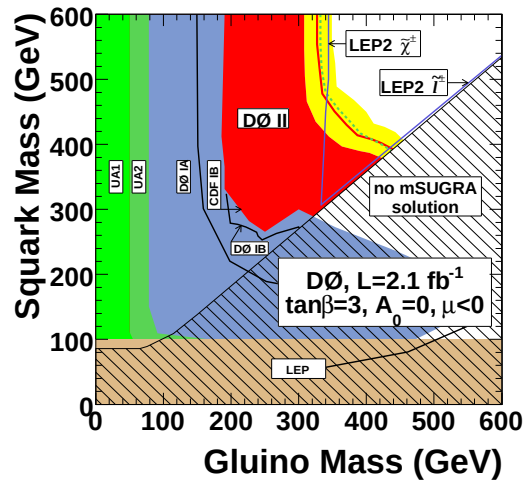

Figure 4. DØ mass exclusion in the $m_{\tilde{q}}$-$m_{\tilde{g}}$ plane.

conserving models [7], sparticles are produced in pairs and the lightest supersymmetric particle (LSP) is stable and denoted $\tilde{\chi}_1^0$.

3.1. $\tilde{b}\bar{\tilde{b}}$ Production

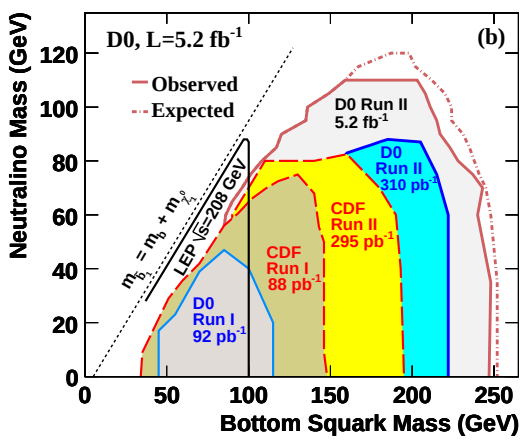

Figure 5. DØ exclusion plot in the $m_{\tilde{\chi}_1^0}$-$m_{\tilde{b}}$ plane.

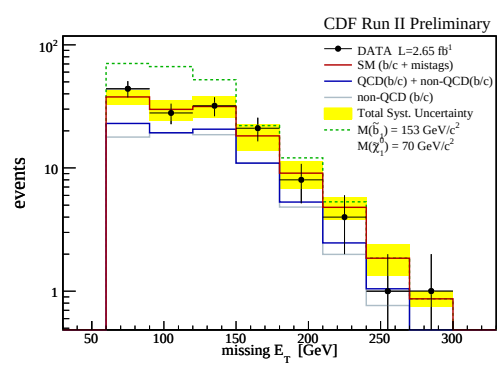

Figure 6. CDF $\not\!\!E_T$distribution.

Assuming a SUSY particle mass hierarchy such that the $\tilde{b}$ decays exclusively as $\tilde{b} \rightarrow b\tilde{\chi}_1^0$, the expected signal for direct $\tilde{b}\bar{\tilde{b}}$ production is characterized by the presence of two energetic jets from the hadronization of the bottom quarks and large $\not\!\!E_T$from the two LSPs in the final state.

In the DØ analysis [8], an artificial neural network (NN) is used to identify jet associated with b quarks. Final states with 2 or 3 jets are selected. Additional requirements that the two

leading jets are identified b jets and large $\not\!\!E_T$are imposed. This result is based on 5.2 fb^{-1} of integrated luminosity.

In the CDF analysis [9], b quarks are identified via displaced vertices. Final state with 2 jets, with at least one identified as a b quark are selected. Further optimization is done in two signal regions: $m_{\tilde{b}} - m_{\tilde{\chi}_1^0} < 90$ GeV and $m_{\tilde{b}} - m_{\tilde{\chi}_1^0} > 90$ GeV. This result is based on 2.65 fb^{-1} of integrated luminosity.

Figure 6 show the agreement of the data and SM expectation in the CDF analysis. Both experiements see agreement with SM expectations. Figure 5, show the mass exclusion in the $m_{\tilde{\chi}_1^0}$-$m_{\tilde{b}}$ plane. Assuming a massless $\tilde{\chi}_1^0$, DØ constrains $m_{\tilde{b}} > 247$ GeV. Assuming $m_{\tilde{\chi}_1^0} < 80$ GeV, CDF constrains $m_{\tilde{b}} > 230$ GeV.

3.2. $\tilde{t}\bar{\tilde{t}}$ Production

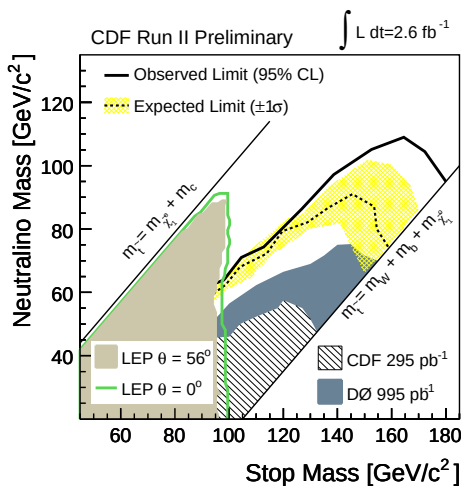

Figure 7. CDF exclusion in the $m_{\tilde{\chi}_1^0}$-$m_{\tilde{t}}$ plane.

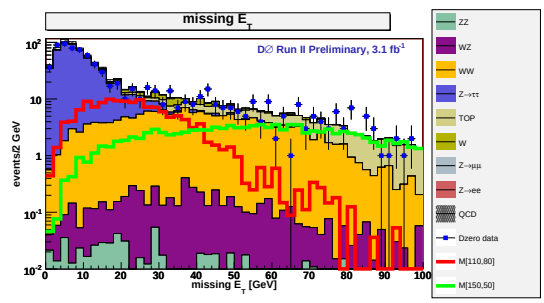

Figure 8. DØ $\not\!\!E_T$ distribution.

In the MSSM, the mixing between the chiral states of the scalar partner particles of the SM fermions is greatest for the top quark due to its large mass. Thus, it is possible that the light stop is the lightest squark and has the largest production cross section at the Tevatron. If R-parity is conserved, then the top squarks would be produced in pairs with the dominant diagrams being quark/anti-quark annihilation and gluon/gluon fusion. If the two body decays $\tilde{t} \to b\tilde{\chi}_1^0$ and $\tilde{t} \to t\tilde{\chi}_1^0$ are kinematically forbidden, then the likely decay modes are the two body $\tilde{t} \to c\tilde{\chi}_1^0$, the three body $\tilde{t} \to b\tilde{\nu}^0 l^+$, and the four body $\tilde{t} \to b\tilde{\chi}_1^0 f\bar{f}$.

In the DØ analysis [10], we search for the three body decays of top squark pairs in the in the $b\bar{b}e^{\pm}\mu^{mp}\tilde{\nu}\nu$ final state. The analysis also assumes $\tilde{t}$decay via the three body decay mode with a 100% branching fraction, and the sneutrino ($\tilde{\nu}^0$) is the LSP, Events with opposite signed e and μ are selected with no requirement on the number of jets. Then selection is further optimized for large and small differences between $m_{\tilde{t}}$ and $m_{\tilde{\nu}}$. Using 3.1 fb^{-1} of integrated luminosity, DØ sees agreement with SM expectations. Figure 8 shows the agreement in the $\not\!\!E_T$for data and SM expectation. For $m_{\tilde{\nu}} < 80$ GeV, DØ constrains $m_{\tilde{t}} > 200$ GeV.

In the CDF analysis [11], we search for the two body decay $\tilde{t} \to c\tilde{\chi}_1^0$. Here we make the assumption that the two body branching ratio is 100%, and the $\tilde{\chi}_1^0$ is the LSP. A NN based flavor separator is used to identify jets coming from c quarks. Events with 2 jets and $\not\!\!E_T$are

selected. Additionally, one of the jet is required to be identified as a c quark. The sensitivity is futher optimized with a NN to separate the signal like events from background like events. Using 2.6 fb^{-1} of integrated luminosity, CDF sees agreement with SM expectations. Figure 7 shows the limit in the $m_{\tilde{\chi}_1^0}$-$m_{\tilde{t}}$ plane. Assuming $m_{\tilde{\chi}_1^0} = 80$ GeV CDF constrains $m_{\tilde{t}} > 180$ GeV.

4. GMSB Di-photon

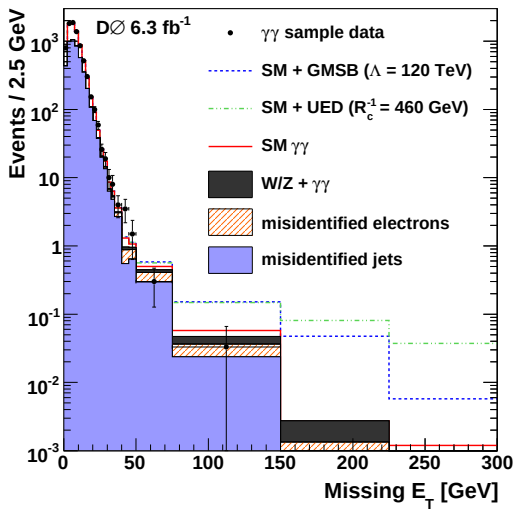

Figure 9. DØ $\not\!\!E_T$distribution.

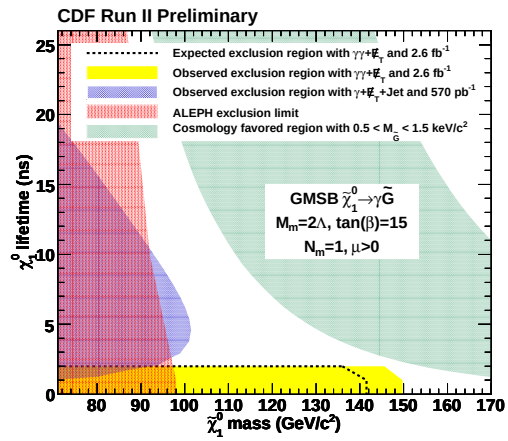

Figure 10. CDF exclusion limit in the $\tilde{\chi}^0_{1lifetime}$-$m_{\tilde{\chi}_1^0}$ plane.

In gauge mediated supersymmetry (SUSY) breaking (GMSB) models, the masses of the particles arise from SM gauge interactions and are proportional to the effective SUSY breaking scale L. As the gravitino ($\tilde{G}$) does not participate in SM gauge interactions, it has a small mass [12] and is the LSP. Assuming R-parity conservation, the SUSY process with the largest cross section at the Tevatron would be chargino and neutralino production, followed by decay chains to the next-to-lightest SUSY particle (NLSP).We consider the case when the lightest neutralino ($\tilde{\chi}_1^0$) is the NLSP, and decays promptly with the dominant branching fraction yielding a photon (γ) and an essentially massless gravitino. The two gravitinos escape detection, resulting in the final state $\gamma\gamma + \not\!\!E_T + X$ where X denotes leptons and jets produced in the decay chains.

Using 6.3 fb^{-1} and 2.6 fb^{-1} of data respectively, DØ [13] and CDF [14] see agreement with SM expectations. Figure 9 shows the data and SM expectation for $\not\!\!E_T$in the DØ data. Figure 10 show the exclusion limit in the $\tilde{\chi}^0_{1lifetime}$-$m_{\tilde{\chi}_1^0}$ plane. DØ constrains $m_{\tilde{\chi}_1^0} > 175$ GeV and CDF constrains $m_{\tilde{\chi}_1^0} > 149$ GeV.

5. Hidden Valley Dark Photon

Hidden-valley models [15] contain a hidden sector that is very weakly coupled to SM particles. The force carrier in the hidden sector, the dark-photon (γ_D), must have a mass below ~2 GeV, and generally decays into SM charged-fermion pairs. In many models, γ_D has a short lifetime, and does not travel an observable distance before decaying. Assuming SUSY, there will be partners for both the SM and the hidden sector particles, and this can lead to decay chains as shown in Figure 11 Since hidden-sector particles have small mass and they are produced with high velocities, their decays through the hidden sector can produce jets of tightly collimated particles from decays of γ_D. If the γ_D is less than the mass of $2 \times m_\pi$ the jets will consist only

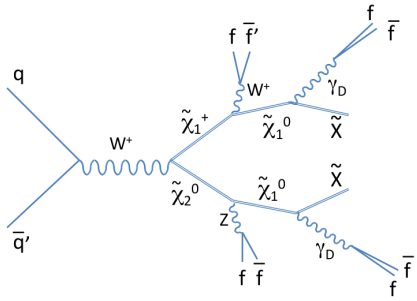

Figure 11. DØ Feynmann diagram for γ_D decaying to lepton jets.

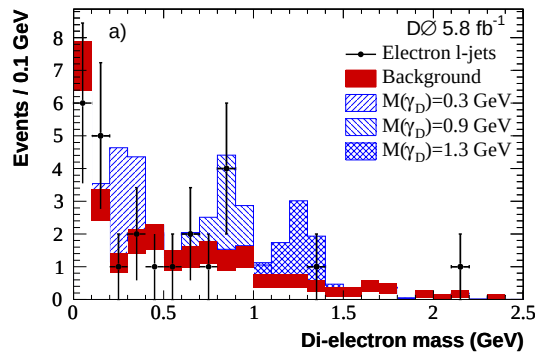

Figure 12. DØ ee invariant mass.

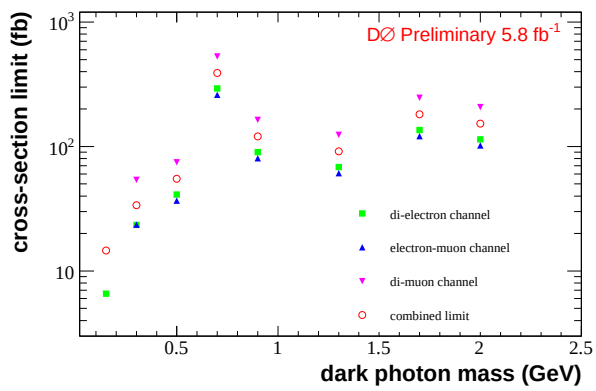

Figure 13. DØ Cross section limit as a function of γ_D mass.

of charged leptons. Even for larger m_{γ_D}, the lepton content of these jets will be high, and we therefore refer to them as leptonic jets (l-jets).

Using 5.8 fb^{-1} of data, DØ uses l-jets in association with large $\not{E}_T$ to search for γ_D [16]. While no evidence of signal was found, we are able to set cross section limits on SUSY events decaying to two l-jets and $\not{E}_T$, Figure 13.

6. R_p Violating (RPV) Tau Sneutrino ($\tilde{\nu}_\tau$)

In some SUSY models [17], the R-parity which differentiates standard model particles from their supersymmetric partners could be violated in the most general representation of the super potential. Such models can introduce lepton favor violation and provide non-zero neutrino masses and angles consistent with neutrino-oscillation data.

In the DØ analysis [18], events with one e and one μ are selected. Further requirement are such as removing events with jets are used to suppress SM backgrounds. Figure 15 shows the agreement between data and SM backgrounds. Since no excess is observed, we set a limit on the cross section times branching ratio, Figure 14.

In the CDF analysis [19] all conbinations of different flavor leptons are used ($e\mu$, $e\tau$, $\mu\tau$). Using an intigrated luminosity of 1 fb^{-1} CDF see agreement with the SM expectation. Assuming a certain set of coupling parameters, we set a lower limit on the mass of the $\tilde{\nu}_\tau$ of 441 GeV.

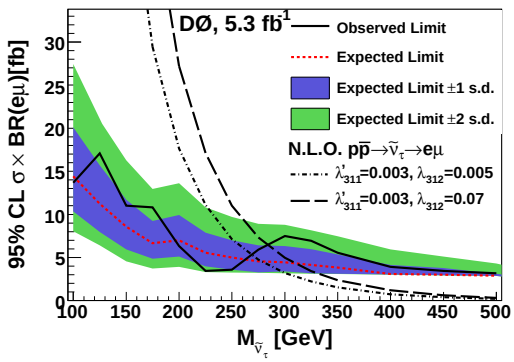

Figure 14. DØ $\tilde{\nu}_\tau$ exclusion.

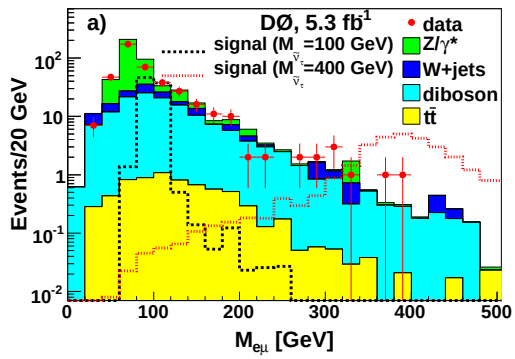

Figure 15. DØ $e\mu$ invariant mass.

7. Summary

The Tevatron is collecting high quality data at an unprecedented rate and both CDF and DØ are doing their best to probe new models. While there is currently no evidence of new physics, we are able to set limits on several particle masses within a variety of SUSY models.

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