Numerous searches for evidence of supersymmetry at the Tevatron have been performed by the CDF and DØ collaborations. Recent results are presented here including squarks and gluinos in jets and missing transverse energy, stop in several different decay modes, charginos and neutralinos in trileptons, neutralinos in di-photons, R-parity violating sneutrinos in $e^+\mu$ events, and long-lived particles. These explore many variations of SUSY such as MSSM, mSUGRA, and GMSB. While no evidence of SUSY production is observed, 95% CL limits on cross sections and SUSY parameter space are set. Most of these limits are the world’s best.

1. INTRODUCTION

Of the many Beyond the Standard Model (BSM) theories, supersymmetry (SUSY) is one of the most investigated models. SUSY provides a possible solution to the hierarchy problem [1] and is a necessary component of string theory. SUSY proposes a new symmetry between fermions and bosons that doubles the number of particles. This symmetry introduces a new multiplicative quantum number, $R$-parity ($R_p$). Supersymmetric particles have $R_p = -1$, while normal (non-SUSY) particles have $R_p = +1$.

SUSY comes in many varieties (see M. Perelstein’s contribution to these proceedings for a review of recent theoretical work). The mechanism responsible for supersymmetry breaking creates many of these variations including mSUGRA (super-gravity), GMSB (gauge-mediated supersymmetry breaking), and AMSB (anomaly-mediated supersymmetry breaking). If $R_p$ is conserved then SUSY particles must be produced in pairs at the Tevatron and cascade down to the lightest supersymmetric particle (LSP) which is stable. The LSP then becomes a dark matter candidate, simultaneously solving problems in particle physics and astronomy.

At the Fermilab Tevatron, supersymmetry has been searched for in a wide variety of channels, some that complement previous LEP searches and some that explore completely new territory. Here we present many of the latest results. This proceedings is divided into two categories which are label “natural” SUSY (Sec. 2) and “unnatural” SUSY (Sec. 3). These are labels applied by the author and not intended to be used as formal definitions. All limits quoted are at the 95% CL. For a complete review of Tevatron Run II searches (including Higgs) through the first seven years of running see [2].

2. “NATURAL” SUSY

What is categorized here as “natural” SUSY are models where $R_p$ is conserved and all SUSY particles (other than the LSP) promptly decay. Since astronomical bounds require a stable LSP to be neutral [3], LSP candidates are generally the lightest neutralino ($\chi_1^0$), the sneutrino ($\tilde{\nu}$) or the gravitino ($\tilde{G}$). The prompt decays ensure that all particles observed directly in the detector are non-supersymmetric and originate from the production vertex. The LSP will escape the detector without interacting resulting in a missing transverse energy signature.

2.1. Squarks and Gluinos

At hadron colliders (such as the Tevatron), strong interactions tend to dominate production processes. Therefore, squarks and gluinos may have the highest production rates, if their masses are not too much larger than other SUSY particles. Then if the squark mass is significantly less than the gluino, squark pair production dominates. In the
opposite case, gluino pair production is largest. Finally, if the masses are similar, squark+gluino production becomes important (see Fig. 1).

The primary decay modes are ˜q → qχ^0_1 and ˜g → q̅q̅χ^0_1. Therefore, each of these mass conditions leads to a different experimental signature of two to four primary jets from decays. Additional jets can be found in the event from misreconstruction or initial/final state radiation. The generic signature is multiple jets with missing transverse energy (E_T). In order to optimize sensitivity three concurrent analyses are carried out looking for (a) two or more jets, (b) three or more jets, and (c) four or more jets. Events that fall into more than one sample are accounted for in the combination.

Both CDF and DØ have performed searches for squarks and gluinos with more than 2 fb^{-1} of Run II data [4, 5]. Events are selected with multiple high-p_T jets and large missing transverse energy. The mSUGRA model is used with A_0 = 0, μ < 0, and tanβ = 3 for DØ and 5 for CDF to simulate signal. For each of the jet multiplicities, the analyses are optimized for final selection on jet p_T, E_T, and total energy. No significant excess of data is observed. Figure 2 shows the interpretation of the analysis as limits on the squark versus gluino mass plane within the mSUGRA model.

The large top quark mass contributes to the stop mass to generally cause it to be the lowest mass squark. It also causes the ˜t → tχ^0_1 decay to be suppressed, therefore allowing other decay modes of interest. Therefore each collaboration has performed dedicated stop searches.

The DØ collaboration has searched for stop in events with an electron, a muon, two or more jets and large missing transverse energy [7]. The different type leptons leads to a higher branching ratio and lower backgrounds in a search for the decay ˜t → t̃b̃ν where ̃ν is the LSP. The selected events were binned two dimensionally in the variables Σp_T(jets) and p_T(µ) + p_T(e) + E_T. Comparisons of data and expected backgrounds show good agreement. Limits are set in the m_̃ν vs m_̃t parameter space (Fig. 3).

CDF has performed a similar search in the dilepton channel (lepton = e or µ) with the decay mode ˜t → b̃χ^+_1 → bχ^0_1ν where the ̃χ^0_1 is the LSP [8]. This search is targeted for stop masses below the top mass (m_̃t = 135 – 155 GeV). Good agreement is observed between data and expected background. However, under the assumption that the decay chain is dominated by ̃χ^±_1 → W^±χ^0_1 no limits on stop production are possible. (Note, this analysis has been updated to higher luminosity and to allow for higher branching fractions BR(χ^±_1 → bχ^0_1ν) [8].
Another stop search by DØ looked for the decay mode $\tilde{t} \to c\tilde{\chi}^0_1$. If the mass relations $m_{\tilde{t}} < m_t + m_{\tilde{\chi}^0_1}$, $m_{\tilde{t}} < m_b + m_{\tilde{\chi}^0_{\pm}}$ and $m_{\tilde{t}} < m_W + m_b + m_{\tilde{\chi}^0_{\pm}}$ are true, then the flavor-changing charm + $E_T$ is assumed to occur with 100% branching ratio. The analysis selected events with two jets (one of which is tagged as heavy flavor) and large $E_T$. Final selections on $E_T$, $S = \Delta\phi_{\text{max}} + \Delta\phi_{\text{min}}$, and the scalar sum of the $p_T$ of all jets ($H_T$) are optimized for three different stop and neutralino masses. Good agreement between data and background leads to limits in the $m_{\tilde{\chi}^0_1}$ vs $m_{\tilde{t}}$ plane (Fig. 4).

CDF has also studied the heavy flavor + $E_T$ channel by selecting events with at least two jets, one of which must be heavy flavor tagged. This channel is interpreted as a search for both $\tilde{t} \to c\tilde{\chi}^0_1$ and $\tilde{b} \to b\tilde{\chi}^0_1$. The analysis has three separate searches based on the hypothetical stop mass (<100 GeV, 100-120 GeV, and >120 GeV) or sbottom mass (<140 GeV, 140-180 GeV, and >180 GeV). Each channel/mass is optimized and number of data events is compared to the expected background (see Tab. 1). Limits in the neutralino versus stop(sbottom) mass plane are shown in Fig. 5.
Table I: Number of data and expected background events for the CDF heavy flavor + $E_T$ analysis. The left table shows the stop analysis while the right table is for the sbottom analysis.

| $m(\tilde{t})$ | Expected Background | Data  |
|---------------|---------------------|-------|
| <100 GeV      | 137 ± 6.2 ± 14.6    | 151   |
| 100-120 GeV   | 94.9 ± 5.0 ± 9.9   | 108   |
| >120 GeV      | 42.7 ± 2.6 ± 4.6   | 43    |

| $m(\tilde{b})$ | Expected Background | Data  |
|----------------|---------------------|-------|
| <140 GeV       | 55.0 ± 4.2 ± 5.9    | 60    |
| 140-180 GeV    | 17.8 ± 1.7 ± 1.6   | 18    |
| >180 GeV       | 4.7 ± 2.1 ± 0.5    | 3     |

CDF has also performed a search for gluino production with decay mode $\tilde{g} \rightarrow \tilde{b}\bar{b} \rightarrow b\tilde{\chi}_1^0\bar{b}$ [10]. For gluino pair production, this results in a four $b$-jet final state. The analysis only requires one of the four jets to be tagged as heavy flavor. Because the kinematics are heavily dependent, the analysis is optimized in two separate regions of $\Delta m = m(\tilde{g}) - m(\tilde{b})$. For small $\Delta m$, 19 events are observed for $22.0 \pm 3.6$ expected while at large $\Delta m$, 25 events are observed with $22.7 \pm 4.6$ expected. Limits in the sbottom mass versus gluino mass are shown in Fig. 6.

### 2.2. Charginos and Neutralinos

Associated production of a chargino ($\tilde{\chi}_1^\pm$) and a neutralino ($\tilde{\chi}_2^0$) provides a “golden” search channel through events that have three charged leptons and missing transverse energy (from neutralinos and neutrinos). Very few standard model processes naturally create three isolated leptons, the exception being dibosons such as $WZ$. Other backgrounds tend to be instrumental arising from mis-identified isolated leptons. Due to the three final state charged leptons and three unobserved particles, often the lowest $p_T$ lepton will be difficult to identify cleanly as a lepton. Therefore, the search techniques will allow for it to be observed as an isolated track. This also allows for some acceptance of taus that are not explicitly included.

CDF has performed searches in multiple channels using 2 fb$^{-1}$ of Run II data. Five exclusive channels are ordered by purity according to the quality criteria used to identify the three constituent leptons. They include various The data and expected backgrounds are listed in Table II. Excellent agreement between data and background leads to limits within the mSUGRA model ($m_0 = 60$, $\tan(\beta) = 3$, $A_0 = 0$, $\mu > 0$) that restrict $m(\tilde{\chi}_1^\pm) > 145$ GeV (Fig. 7(left)). The DØ search combines four analyses with 1-1.7 fb$^{-1}$. DØ categorizes its search by lepton type ($e$, $\mu$ or track) and also includes a search in same-sign muons that does not require the third lepton to be observed.
Figure 5: Limits on neutralino versus stop (left) and sbottom (right) masses from the CDF search in the heavy flavor \( + E_T \) channel.

Figure 6: Limits on the sbottom and gluino masses from the CDF search for gluino production.

\( (\text{Tab. III}) \).

\[ \text{DØ uses a variation of mSUGRA with no slepton mixing. In a version that maximizes decays to } e \text{ and } \mu \text{ (called } 3\ell \text{ max), a limit of } m(\chi_{1}^{\pm}) > 145 \text{ GeV is also observed (Fig. 7 (right)).} \]

In the GMSB model, the LSP is the gravitino \( (\tilde{\chi}) \) which leads to a different decay mode \( \chi_{1}^{0} \rightarrow \gamma \tilde{\chi} \) where the gravitino escapes unobserved. In events with a pair of neutralinos, a distinct SUSY signature of two photons plus large missing transverse energy would be observed. DØ performed a search for such events \( [12] \). Figure 8 (left) shows the \( E_T \) spectrum for events with two photons with \( E_T > 25 \) GeV. Limits on the GMSB model from this data result
Table II: Number of data and expected background events for the CDF trilepton search channels. The lines labeled “Total” are a sum of the lines directly above.

| Expected Background | Data |
|---------------------|------|
| 3 tight             | 0.49 ± 0.04 ± 0.08 | 1 |
| 2 tight, 1 loose     | 0.25 ± 0.03 ± 0.03 | 0 |
| 1 tight, 2 loose     | 0.14 ± 0.02 ± 0.02 | 0 |
| Total trilepton     | 0.88 ± 0.05 ± 0.13 | 1 |
| 2 tight, 1 track     | 3.22 ± 0.48 ± 0.53 | 4 |
| 1 tight, 1 loose, 1 track | 2.28 ± 0.47 ± 0.42 | 2 |
| Total dilepton + track | 5.5 ± 0.7 ± 0.9 | 6 |

Table III: Number of data and expected background events for the DØ trilepton search channels. Here, $\ell$ is an isolated track.

| Expected Background | Data |
|---------------------|------|
| ee$\ell$            | 1.8 ± 0.8 | 0 |
| $\mu\mu\ell$        | 0.3 ± 1.3 | 2 |
| e$\mu\ell$          | 0.9 ± 0.4 | 0 |
| $\mu^+\mu^-$ or $\mu^-\mu^-$ | 1.1 ± 0.4 | 1 |

in $\Lambda > 91.5$ TeV, $m(\tilde{\chi}_0^0) > 125$ GeV, and $m(\tilde{\chi}_1^\pm) > 229$ GeV (Fig. 8 right)). These are significant improvements over the previous limits set from a combination of DØ and CDF results with lower luminosity $^{13}$. CDF has analyzed the diphoton channel (see contribution from S. Yu in these proceedings), but an interpretation within the GMSB framework is still in progress.

3. “UNNATURAL” SUSY

While the above searches primarily explored traditional variations of supersymmetry such as mSUGRA and GMSB with $R_p$ conservation, there are other variations that might exist. Many of these will have different experimental signatures that require separate searches to explore the full parameter space. Two such categories have recently been

![Figure 7: Limits on the cross section times branching ratio from the trilepton analyses of DØ (left) and CDF (right).](image-url)
investigated by CDF and DØ: $R_p$ violation and long-lived (but non-stable) particles. These are discussed below.

### 3.1. R-parity Violating SUSY

While conservation of $R_p$ in supersymmetry can allow for a solution to the dark matter question, there is no *a priori* reason SUSY and dark matter need to be tied together. $R_p$ can be trivially violated by adding terms to the superpotential:

$$W = W_{MSSM} + \frac{1}{2} \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i D_j \bar{D}_k$$

where the first term is the minimal supersymmetric model (MSSM) superpotential with $R_p$ conservation, the second and third terms allow for lepton number violation, the fourth allows for baryon number violation, and $i, j, k$ can have values 1-3 representing the three generations. It is common to assume that for each term, only one $i, j, k$ combination dominates.

DØ has published a search for resonant production of a sneutrino (Fig. 9) where the production vertex is governed by $\lambda'_{311}$ and the decay vertex by $\lambda_{132}[15]$. In this case, the sneutrino decays to an electron and a muon. The $e\mu$ backgrounds are small and arise primarily from $Z \rightarrow \tau\tau$, diboson and top quark production. The search is performed
using the invariant mass of the two particles where evidence of the sneutrino would appear as a peak. Observed data agrees well with expected backgrounds and limits on the cross section times branching ratio are set (Fig. 10).

3.2. Long-lived SUSY Particles

Multiple mechanisms exist that can lead to long-lived, but ultimately unstable, charged or neutral particles in BSM theories. For a review of Run II searches for long-lived particles at the Tevatron, see [14]. Recently CDF has performed two such searches with SUSY interpretations.

The first search looked for a charged, massive, stable particle (nicknamed CHAMPs) where stable means sufficiently long-lived to escape the detector prior to decay [16]. Because the particles are massive, they will tend to move slower than the speed of light and also will deposit more energy than a minimum ionizing particle moving at $c$. However, they are likely to reach the muon system. Therefore, CDF searched for particles in the muon system, measured their time of flight (velocity) and momentum, and calculated their mass. Figure 11(left) shows the observed mass spectrum. Since no standard model CHAMP exists, data is used to estimate the background to the signal region. A stable stop that has hadronized is used as signal and limits on the production cross section are set (Fig. 11) which leads to a stop mass limit of $>250 \text{ GeV}$.

A second search looked for signals from photons that arrive at the calorimeter later than expected from speed of light [17]. The assumed signal is a long-lived, slow moving, neutral particle that decays to a photon and an unobserved particle. While the search is generally model independent, a GMSB long-lived $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$ model (similar to the GMSB di-photon model above) is used to simulate signal. CDF has instrumented timing for its electromagnetic calorimeter [18]. Figure 12(left) shows the difference between actual arrival time and expected arrival time for photons. Late arriving photons would create an asymmetric tail on the right side of 0. In the signal region of 2-10 ns, two events are observed compared to an expectation of $1.25 \pm 0.66$ events. Limits have been set in the neutralino lifetime versus mass plane (Fig. 12(right)).

4. SUMMARY

The Tevatron experiments DØ and CDF have strong programs to search for evidence of supersymmetry. The analysis techniques have been well developed and optimized with a good understanding of the detector and backgrounds. With larger data sets available and being recorded, even more interesting results are on their way. In addition, there are expectations that several results (such a trileptons, squarks and gluinos, GMSB SUSY) can be combined between
the experiments giving an immediate doubling of the effective luminosity. While no evidence of SUSY has been found at the Tevatron, many of the best available limits have been produced by the CDF and DØ collaborations.

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