SUSY Searches Using Photons at the Tevatron

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We report on recent searches by the CDF and DØ collaborations for physics beyond the Standard Model, using events with one or more photons with high transverse momentum. These searches were conducted using the complete 1992–1996 data sample, corresponding to an integrated luminosity in excess of 100 pb^{-1} per experiment. In all cases, the searches have null results, with the possible exception of a single $ee\gamma\gamma\not{E}_T$ candidate seen by the CDF collaboration. These null results are interpreted to exclude parts of the parameters spaces of several models of supersymmetry.

1 Introduction

Supersymmetry (SUSY) is a symmetry relating fermions and bosons.[1] It introduces for every particle in the Standard Model a partner with the same quantum numbers, but with spin differing by one half. Recent suggestions[2,3] have been made that SUSY may result in signatures containing one or more high transverse momentum photons. Some of this interest is a result of the observation of one event containing two high transverse energy photons, two electron candidates, and a large imbalance in transverse energy ($\not{E}_T$) by the CDF collaboration.[4] We present here a summary of recent analyses by the CDF and DØ collaborations searching for such signatures. In these analyses, we assume that R-parity is conserved. (R-parity [5] is a multiplicative quantum number, +1 for Standard Model particles and −1 for their superpartners.) Therefore, superparticles are produced in pairs, and the lightest supersymmetric particle (LSP) is stable.

In the MSSM, the gaugino-Higgsino sector (excluding gluinos) is described by four parameters: M_1 (the U(1) gaugino mass parameter), M_2 (the SU(2) gaugino mass parameter), μ (the Higgsino mass parameter), and $\tan(\beta)$(the ratio of the vacuum expectation values of the two Higgs doublets). The MSSM can be further constrained by demanding unification of the gaugino masses M_2 and M_1 at some GUT scale, which results in the relation $M_1 = \frac{5}{3} M_2 \tan^2\theta_W$. It can be further constrained by the requirement that the magnitude of μ (but not its sign) be determined by electroweak symmetry breaking. Each of these possibilities is considered by at least on of the analyses described herein.

Photons occur in different SUSY models for a variety of reasons. For models in which SUSY is broken by a gauge interaction (GMSB models), the LSP is the gravitino ($\widetilde{G}$). The mass of the gravitino is of order $4.2 \times 10^{-5}(\Lambda/500)^2$ eV, where Λ is the SUSY breaking scale in GeV. For a typical SUSY breaking scale of 100 TeV, this yields a gravitino mass of a few electron volts. In many GMSB models, the next lightest superpartner is the lightest neutralino, $\widetilde{\chi}_1^0$. In such models, the signature of SUSY production is the production of two $\widetilde{\chi}_1^0$s (either directly, or through the decay of other SUSY particles), with the subsequent decay $\widetilde{\chi}_1^0 \to \gamma\widetilde{G}$; the observable effect is the production of two high transverse momentum photons and missing transverse momentum.

Photons can also appear in models without GMSB (in which the $\widetilde{\chi}_1^0$ is the LSP), for example, in the radiative decay $\widetilde{\chi}_2^0 \to \gamma\widetilde{\chi}_1^0$. In part of the parameter space of the minimal supersymmetric extension of the Standard Model (MSSM), this decay is dominant [6]; this has been proposed as a possible explanation for the CDF $ee\gamma\gamma\not{E}_T$ candidate.[3] Within the MSSM, the radiative decay $\widetilde{\chi}_2^0 \to \gamma\widetilde{\chi}_1^0$ dominates in the region of parameter space defined by $50 \le M_1 \sim M_2 \le 100$ GeV/c^2, $1 \le \tan(\beta) \le 3$, and $-65 \le \mu \le -35$ GeV/c^2.[6]

The SUSY searches presented here fall into two types: diphoton searches, covered in Section 2 and photon + $\not{E}_T$ searches, covered in Section 3.

2 SUSY Searches Using Two Photons

2.1 CDF Results

The CDF collaboration has published a search for events with two high transverse energy photons.[4] Using a data sample corresponding to an integrated luminosity of 85 pb^{-1}, they searched for events with two isolated photons with $E_T > 12$ GeV in the central region ($|\eta^\gamma| < 1.0$). Each photon candidate was required to have no associated track with $p_T > 1$ GeV/c, and no more than one associated track with $p_T < 1$GeV/c, a shower shape consistent with a single photon, and no other photon candidate within the same 15° segment of the calorimeter. To maintain the project geometry of the calorimeter, the primary collision vertex was required to be within 60 cm of the center of the detector. To suppress cosmic rays, events

were required to have no central hadronic calorimeter tower with $E > 1$ GeV outside of a 56 nsec time window. For events in which both photon candidates had $E_T > 22$ GeV, the fiducial and isolation cuts were loosened. The efficiency for identifying an isolated photon was measured with a control sample of 2663 $Z \to ee$ decays to be $68 \pm 3\%$ for the 12 GeV selection criteria, and $84 \pm 4\%$ for the 22 GeV criteria. This selection resulted in a diphoton sample of 2239 events, with a prompt photon purity of $15 \pm 4\%$.

In order to minimize the effect of fluctuations in jet measurements, events with an jet with uncorrected $E_T > 20$ GeV within 10° in azimuth of the $\not\!\!E_T$ were rejected. The Standard Model processes which contribute to this background contain no intrinsic $\not\!\!E_T$, and thus the $\not\!\!E_T$ distribution from the Standard Model processes can be predicted from the resolution of the detector. Figure 1 shows the $\not\!\!E_T$ distribution of both the "low-threshold" and "high-threshold" samples, compared with that predicted from the detector resolution. Neither distribution shows a significant excess of events beyond the prediction. Note that the events in the "high-threshold" sample are a subset of those in the "low-threshold" sample. The one event containing large $\not\!\!E_T$ (55 ± 7 GeV) appears in both plots.

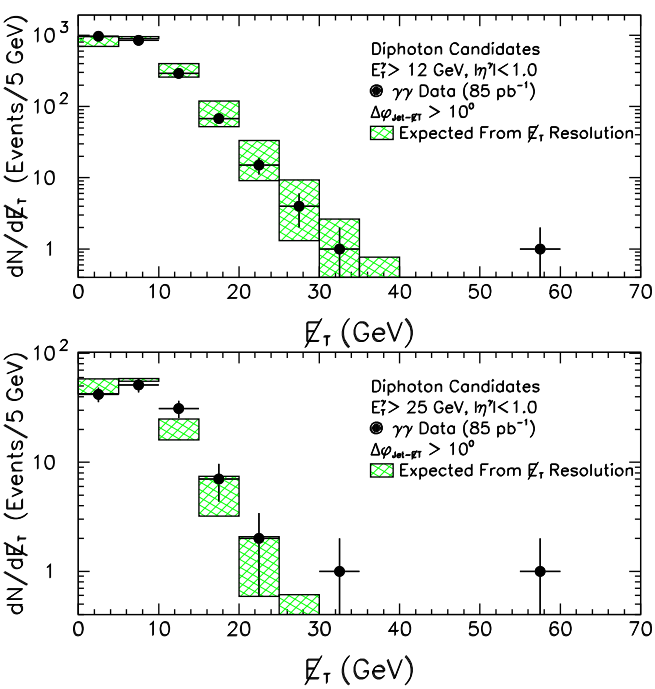

Figure 1: The $\not\!\!E_T$ spectra for events with two central photons, from the CDF experiment. The top (bottom) plot contains events with two central photons with E_T above 12 (25) GeV.

This event has, in addition to the two high E_T photons and large $\not\!\!E_T$, a central electron and an electromagnetic cluster in the plug calorimeter which passes the electron identification criteria used for Z-boson identification.[7] The total p_T of the 4-cluster system is 48 ± 2 GeV/c, opposite to the $\not\!\!E_T$ and in good agreement with the measured magnitude, implying the imbalance is intrinsic to the 4-cluster system. Although the cluster in the plug calorimeter passes all standard electron selection criteria, there is no track in the silicon vertex system pointing directly at the cluster, as would be expected if the cluster were due to an electron. Interpretation of the cluster as coming from an isolated photon, the hadronic decay of a τ, or a jet, while possible, each have expectations less than a few percent. The origin of the cluster remains unclear.

CDF used these data to set limits on two SUSY models, one in which the photons appear from the radiative decay $\tilde{\chi}_2^0 \to \gamma\tilde{\chi}_1^0$, and one model with light gravitinos, in which the photons result from the decay $\tilde{\chi}_1^0 \to \gamma\tilde{G}$. Comparison with SUSY predictions was done using simulated event samples created with SPYTHIA.[8]

To investigate the $\tilde{\chi}_2^0 \to \gamma\tilde{\chi}_1^0$ model of Ref [3] with $m_{\tilde{\chi}_1^0} = 36.6$ GeV/c^2 and $m_{\tilde{\chi}_2^0} = 64.6$ GeV/c^2, CDF simulated both direct production and cascade decays, yielding a prediction of 2.4 events passing the selection criteria of $E_T^\gamma > 12$ GeV and $\not\!\!E_T > 35$ GeV. In the data, one event passes these requirements; consequently, this model could not be ruled out at the 95% confidence level (C.L.). With no background subtraction, the resulting 95% C.L. upper limit on the cross section is 1.1 pb.

In the model with a light gravitino, diphoton production is dominated by $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ production. In the MSSM, further constrained to have the magnitude of μ determined by electroweak symmetry breaking, and by requiring gauge unification for the SU(2) and U(1) symmetries, the parameter space important to the gaugino sector (excluding gluinos) is spanned by M_2, $\tan(\beta)$, and the sign of μ. Variation of these parameters over the range $1 < \tan(\beta) < 25$, $M_2 < 200$ GeV/c^2 for both signs of μ yields the range of cross section limits shown in Figure 2.

2.2 DØ Results

The DØ collaboration has published a search for events with two photons of large transverse energy and large $\not\!\!E_T$.[9] This search was conducted in the context of a model with a light gravitino, with the assumption of gaugino mass unification at the GUT scale.

The $\tilde{\chi}_1^0$ is assumed to be short-lived, decaying to $\gamma\tilde{G}$ in the volume of the detector with branching fraction of 100%. Since R-parity conservation is assumed, the noninteracting $\tilde{G}$ is stable. Pair production of gauginos thus yields events with high E_T photons and large $\not\!\!E_T$, with or without jets.

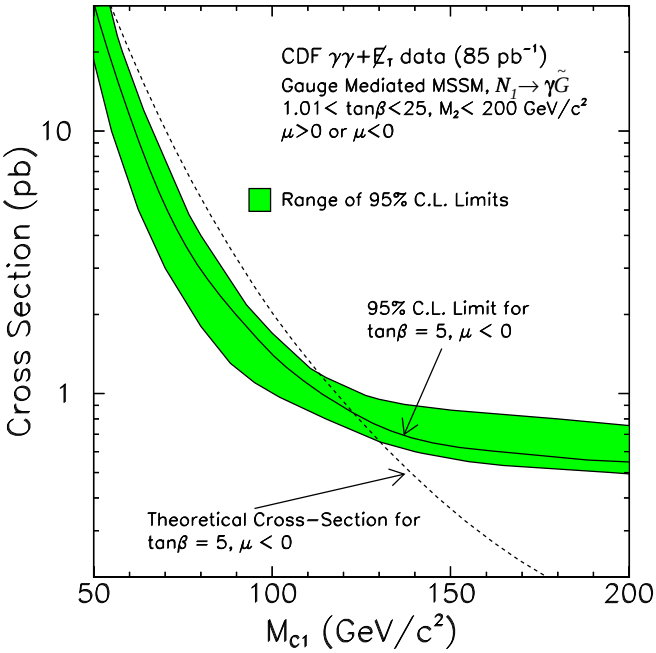

Figure 2: From CDF, the 95% C.L. upper limits on the cross section for the production of $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_1^{\mp}$ and $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^{0}$ for a model with a light gravitino. The shaded region shows the range of cross section limits as the parameters are varied within the limits $1 < \tan(\beta) < 25$ and $M_2 < 200$ GeV/c^2, for both signs of μ. The solid (dashed) line shows the cross section limit (predicted cross section) for the lowest value of $m_{\widetilde{\chi}_1^{\pm}}$ that is excluded: $m_{\widetilde{\chi}_1^{\pm}} < 120$ GeV/c^2 for $\tan(\beta) = 5$ and $\mu < 0$.

The data for this analysis were collected during the 1992–1996 run of the Tevatron collider and represent an integrated luminosity of 106.3 ± 5.6 pb^{-1}. Photon identification consisted of a two-step process: the selection of isolated electromagnetic (EM) clusters, and the rejection of electrons. The EM clusters are selected from calorimeter energy cluster by requiring at least 95% of the energy of the cluster be deposited in the EM section of the calorimeter, for the longitudinal and transverse shower shapes to be consistent with that of a single photon or electron, and by an isolation requirement in the calorimeter. Electrons are then suppressed by rejecting those clusters which have either a reconstructed track or a large number of tracking chamber hits in a road between the calorimeter cluster and the event vertex.

To be selected as a $\gamma\gamma\not{E}_T$ candidate, an event was required to have two identified photons, one with $E_T > 20$ GeV and the second with $E_T > 12$ GeV, each in the pseudorapidity interval $|\eta| < 1.2$ or $1.5 < |\eta| < 2.0$, and $\not{E}_T > 25$ GeV. Two events satisfied all requirements.

The principal backgrounds are events from Standard Model processes with misidentified photons or mismeasured $\not{E}_T$, or both. The background due to mismeasured $\not{E}_T$ was determined from the data using events with EM clusters satisfying looser requirements that used for photon identification, and for which at least one cluster failed the shower profile requirement; these events are expected to have a $\not{E}_T$ resolution similar to that of the diphoton sample. By normalizing the number of events in this sample with $\not{E}_T < 20$ GeV to that observed in the diphoton sample, DØ obtained a background estimate of 2.1 ± 0.9 due to $\not{E}_T$ mismeasurement with $\not{E}_T > 25$ GeV. Other background sources include events with real $\not{E}_T$ and with an electron misidentified as a photon. Taking into account the probability for an electron to be misidentified as a photon (0.45 ± 0.08%, as determined from $Z \to ee$ data), DØ estimated a total of 0.2 ± 0.1 events from such sources, for a total expectation of 2.3 ± 0.9 events from Standard Model background sources. The $\not{E}_T$ distribution of the data sample (before imposition of the $\not{E}_T$ cut) and the expectation from background is compared with that of two SUSY samples in Figure 3.

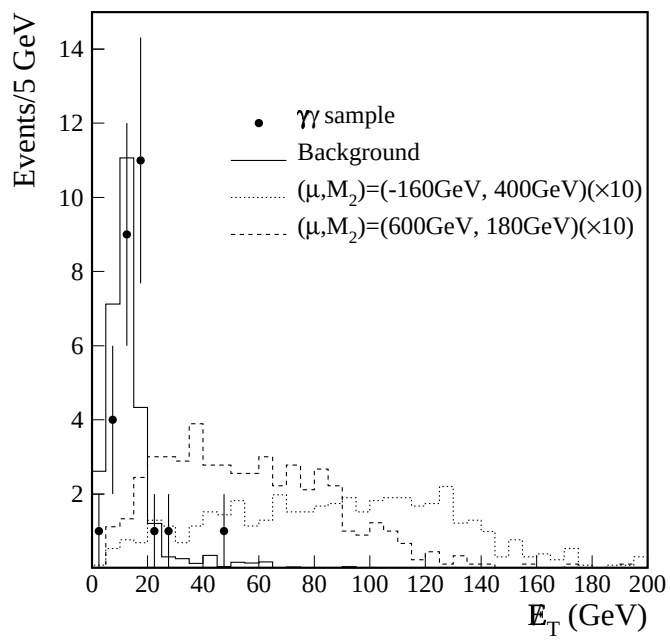

Figure 3: The $\not{E}_T$ distribution of the $\gamma\gamma$ and background samples from the DØ experiment. The number of events with $\not{E}_T < 20$ GeV in the background sample is normalized to that in the $\gamma\gamma$ sample. Also shown are the expected distributions (multiplied by 10) from two representative points in the SUSY parameter space, with $\tan(\beta) = 2$.

DØ modeled chargino and neutralino production and decay using SPYTHIA. They explored the parameter space in the (μ, M_2) plane while keeping $\tan(\beta)$ fixed, generating $\widetilde{\chi}_i^0\widetilde{\chi}_j^0$, $\widetilde{\chi}_i^0\widetilde{\chi}_j^{\pm}$ and $\widetilde{\chi}_i^{\pm}\widetilde{\chi}_j^{\mp}$ events for many points in the (μ, M_2) mass plane. The total signal efficiency varied from ~ 0.01% to ~ 26%, depending on the masses of $\widetilde{\chi}_1^{\pm}$ and $\widetilde{\chi}_1^0$ and their mass difference. With two events observed and 2.3 ± 0.9 events expected from background,

the result was used to calculate a 95% C.L. upper limit on the cross section for chargino and neutralino production; the upper limit varied from several hundred pb for light charginos or neutralinos to 0.18 pb for heavy charginos or neutralinos. Figure 4 shows this limit expressed in the (μ, M_2) parameter plane, for values of $\tan(\beta)$ from 1.05 to 100. DØ obtains a 95% C.L. lower limit on the mass of $\tilde{\chi}_1^{\pm}$ of 150 GeV/c^2, and 77 GeV/c^2 for $\tilde{\chi}_1^0$.

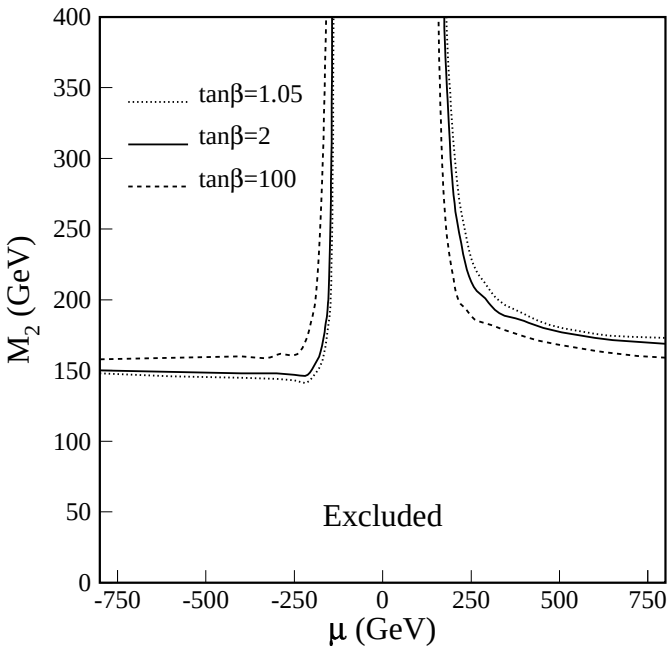

Figure 4: From DØ, the 95% C.L. bounds in the (μ, M_2) plane for $\tan(\beta) = 1.05$ (dotted line), $\tan(\beta) = 2$ (solid line), and $\tan(\beta) = 100$ (dashed line).

3 SUSY Searches Using One Photon

3.1 DØ Results

DØ has submitted for publication [10] a search for events with one high transverse energy photon, two or more jets, and large missing E_T, motivated by recent suggestions [2,3] suggestions that SUSY may result in signatures involving one or more photons in association with multiple jets and $\not\!\!E_T$. They interpret the result in terms of squark and gluino production in the context of SUSY models with a dominant $\tilde{\chi}_2^0 \to \gamma\tilde{\chi}_1^0$ decay.

Within the MSSM, the radiative decay $\tilde{\chi}_2^0 \to \gamma\tilde{\chi}_1^0$ dominates[6] in the region of parameter space defined by $50 \leq M_1 \sim M_2 \leq 100$ GeV/c^2, $1 \leq \tan(\beta) \leq 3$, and $-65 \leq \mu \leq -35$ GeV/c^2.

The data used in this analysis were collected with the DØ detector during the 1992–1996 run of the Tevatron, and represent an integrated luminosity of 99.4 ± 5.4 pb^{-1}. To be selected as a $\gamma\not\!\!E_T + 2$ jets candidate, an event was required to have at least one identified photon with $E_T > 20$ GeV and $|\eta| < 1.1$ or $1.5 < |\eta| < 2.0$, and two or more jets reconstructed with cones of radius $\mathcal{R} = 0.5$, having $E_T > 20$ GeV and $|\eta| < 2.0$. The $\not\!\!E_T$ distribution for events satisfying these requirements is compared with the prediction from Standard Model backgrounds and two different SUSY samples in Fig. 5. The turn-on at low $\not\!\!E_T$ is caused by a trigger requirement of $\not\!\!E_T > 14$ GeV; to avoid this region, $\not\!\!E_T > 25$ GeV was required. A total of 318 events satisfied all requirements.

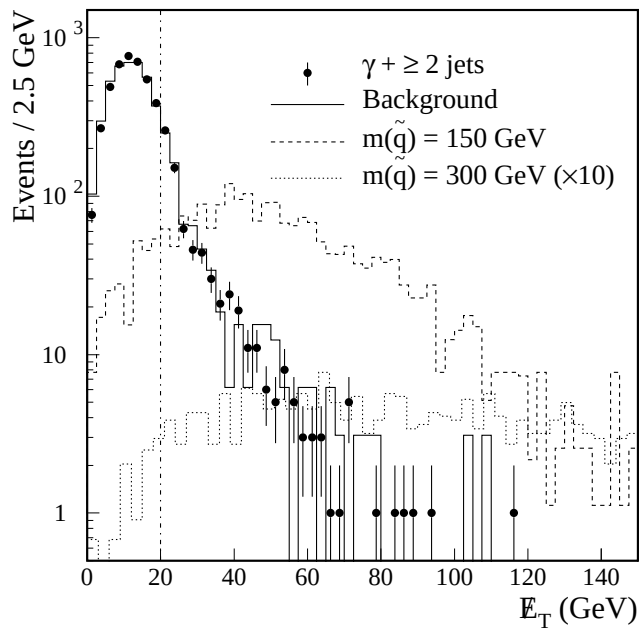

Figure 5: The $\not\!\!E_T$ distribution of the DØ γ+2 jet data (solid circles) compared with predicted background (solid histogram). The number of events in the background is normalized to the γ+2 jets sample for $\not\!\!E_T < 20$ GeV, the region to the left of the dot-dashed line. Also shown (as dashed and dotted histograms) are the distributions expected from SUSY production for $m_{\tilde{q}} = m_{\tilde{g}} = 150$ GeV/c^2 and 300 GeV/c^2.

The principal backgrounds to the signal are QCD direct photon and multijet events, with mismeasured $\not\!\!E_T$ and either a real photon or a jet misidentified as a photon. Smaller backgrounds include $W \to e\nu$ + jets events, in which the electron is misidentified as a photon, and $W \to \ell\nu$ + jets events, in which one of the jets is misidentified as a photon. The expected number of events from these backgrounds was estimated from the data. Above $\not\!\!E_T = 25$ GeV, the total expectation is 320 ± 30 events; 318 events are observed in the data.

To optimize the selection criteria for the detection of a signal from SUSY, DØ simulated squark and gluino pair production, and production in association with charginos and neutralinos, using SPYTHIA, with $M_1 = M_2 = 60$ GeV/c^2, $\tan(\beta) = 2$, and $\mu = -40$ GeV/c^2, yielding

$m_{\tilde{\chi}_1^0} = 34$ GeV/c^2, $m_{\tilde{\chi}_2^0} = 60$ GeV/c^2, and a branching fraction B of 100% for $\tilde{\chi}_2^0 \to \gamma\tilde{\chi}_1^0$. Defining H_T as the scalar sum of the E_T of all jets with $E_T > 20$ GeV and $|\eta| < 2.0$, the sensitivity to SUSY was increased by selecting $\not{E}_T$ and H_T cutoffs to maximize the ratio of the signal efficiency and the uncertainty in the background prediction. To ensure sensitivity for both high and low squark and gluino masses, the optimization was done for $m_{\tilde{q}} = m_{\tilde{g}} = 150$ GeV/c^2 and 300 GeV/c^2; the optimum $(\not{E}_T, H_T)$ values were (35, 100) and (45, 220) at these two points, respectively. The lower cuts were used for squark and gluino masses below 200 GeV/c^2, and the higher values were used above those masses. The number of events passing these cutoffs were 60 and 5, with 75 ± 15 and 8 ± 6 events expected from Standard Model processes.

Having observed no excess, DØ used this result to set a 95% C.L. upper limit on $\sigma(p\bar{p} \to \tilde{q}/\tilde{g} \to \tilde{\chi}_2^0 + X) \times$ B$(\tilde{\chi}_2^0 \to \gamma\tilde{\chi}_1^0)$. Figure 6 shows the limit for the case $m_{\tilde{q}} = m_{\tilde{g}}$, together with the leading order cross section, calculated with SPYTHIA. This excludes squarks and gluinos of equal mass below 310 GeV/c^2 at the 95% CL. In the case of heavy squarks, the resulting gluino mass limit is 240 GeV/c^2; in the case of heavy gluinos, the resulting squark mass limit is 240 GeV/c^2. These limits constrain the models proposed in Ref. [3], but do not exclude all of them.

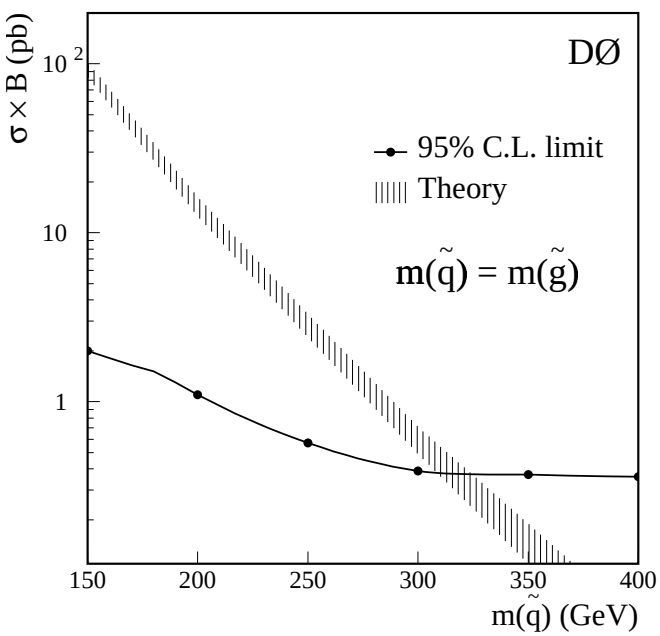

Figure 6: The 95% CL upper limit on $\sigma \times$ B as a function of $m_{\tilde{q}/\tilde{g}}$, assuming equal squark and gluino masses. The hatched band represents the range of expected cross sections for different sets of MSSM parameters, consistent with the constraints B$(\tilde{\chi}_2^0 \to \gamma\tilde{\chi}_1^0) = 100\%$, and $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} > 20$ GeV/c^2.

4 Conclusion

The CDF and DØ experiments have performed a number of searches for supersymmetry in channels involving one or more photons. Although the CDF collaboration has collected one remarkable, and difficult to explain, event, no evidence for supersymmetry has yet been seen. In the absence of such evidence, both collaboration have established new limits in the context of various SUSY models.

Both collaborations are now preparing for the next run of the Tevatron collider, with a greatly increased luminosity. It is clear that SUSY searches involving photons will remain a topic of interest into the next data collection period.

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References

1. Yu.A. Golfand and E.P. Likhtman, *JETP Letters* **13**, 323 (1971); D.V. Volkov and V.P. Akulov, *Phys. Lett.* B **46**, 109 (1973); J. Wess and B. Zumino, *Nucl. Phys.* B **70**, 39 (1974).
2. S. Dimopoulos, S. Thomas and J.D. Wells, *Phys. Rev.* D **54**, 3283 (1996); S. Dimopoulos, M. Dine, S. Raby and S. Thomas, *Phys. Rev. Lett.* **76**, 3494 (1996); K.S. Babu, C. Kolda and F. Wilczek, *Phys. Rev. Lett.* **77**, 3070 (1996); J.L. Lopez, D.V. Nanopoulos and A. Zichichi, *Phys. Rev. Lett.* **77**, 5168 (1996); S. Ambrosanio *et al.*, *Phys. Rev.* D **54**, 5395 (1996); H Baer, M. Brhlik, C.-H. Chen and X. Tata, *Phys. Rev.* D **55**, 4463 (1997).
3. S. Ambrosanio *et al.*, *Phys. Rev. Lett.* **76**, 3498 (1996); S. Ambrosanio *et al.*, *Phys. Rev.* D **55**, 1372 (1997).
4. F. Abe *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **81**, 1791 (1998); F. Abe *et al.* (CDF Collaboration), hep-ex/9806034.
5. G.R. Farrar and P. Fayet, *Phys. Lett.* B **76**, 575 (1978).
6. H.E. Haber, G.L. Kane and M. Quiros, *Phys. Lett.* B **160**, 297 (1985); S. Ambrosanio and B. Mele, *Phys. Rev.* D **55**, 1399 (1997), and erratum, *Phys. Rev.* D **56**, 3157 (1997).
7. F. Abe *et al.* (CDF Collaboration), *Phys. Rev.* D **52**, 2624 (1995).
8. T. Sjöstrand, *Comp. Phys. Commun.* **82**, 74 (1994); S. Mrenna, *Comp. Phys. Commun.* **101**, 232 (1997).

9. B. Abbott *et al.* (DØ Collaboration), *Phys. Rev. Lett.* **80**, 442 (1998).
10. B. Abbott *et al.* (DØ Collaboration), hep-ex/9808010v3, submitted to *Phys. Rev. Lett.*