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Search for Supersymmetry with Gauge-Mediated Breaking in Diphoton Events at D0

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We report the results of a search for supersymmetry (SUSY) with gauge-mediated breaking in the missing transverse energy distribution of inclusive diphoton events using 263 pb^{-1} of data collected by the D0 experiment at the Fermilab Tevatron Collider in 2002–2004. No excess is observed above the background expected from standard model processes, and lower limits on the masses of the lightest neutralino and chargino of about 108 and 195 GeV, respectively, are set at the 95% confidence level. These are the most stringent limits to date for models with gauge-mediated SUSY breaking with a short-lived neutralino as the next-to-lightest SUSY particle.

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Low-scale supersymmetry (SUSY) is one of the most promising solutions to the hierarchy problem associated with the large disparity between electroweak and Planck scales. It stabilizes the Higgs boson mass and postulates that for each known particle there exists a superpartner. Bosons have fermion superpartners and vice versa. None of the superpartners have been observed so far, so superpartner masses must be much larger than that of their partners; i.e., SUSY is a broken symmetry.

Experimental signatures of supersymmetry are determined by the manner and scale of its breaking. In models with gauge-mediated supersymmetry breaking (GMSB) [1,2] it is achieved by the introduction of new chiral supermultiplets, called messengers, which couple to the ultimate source of supersymmetry breaking, and also to the SUSY particles. At colliders, assuming R-parity conservation [3], superpartners are produced in pairs, and then each decays to the next-to-lightest SUSY particle (NLSP), which can be either a neutralino or a slepton. In the former case, which is considered in this Letter, the NLSP decays into a photon and a gravitino (the lightest superpartner in GMSB SUSY models, with mass less than $\sim$1 keV) which is stable and escapes detection, creating an imbalance of the transverse energy in the event. Therefore the signal we are looking for is a final state with two energetic photons and large missing transverse energy ($\not\!\!E_T$).

The differences in event kinematics between particular GMSB SUSY models result in different experimental sensitivities, so in order to obtain quantitative results we consider a model referred to as Snowmass Slope SPS 8 [4]. This model has only one dimensioned parameter Λ that determines the effective scale of SUSY breaking. The minimal GMSB parameters correspond to a messenger mass $M_m = 2\Lambda$, the number of messengers $N_5 = 1$, the ratio of the vacuum expectation values of the two Higgs fields $\tan\beta = 15$, and the sign of the Higgsino mass term $\mu > 0$. The lifetime of the neutralino is not fixed by this model line and is assumed to be sufficiently short to result in decays with prompt photons. Current lower limits on the GMSB neutralino mass for somewhat similar model parameters are 65, 75, and 100 GeV, from the CDF [5], D0 [6], and CERN LEP Collaborations [7], respectively.

We search for SUSY production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV at the Fermilab Tevatron Collider. The D0 detector comprises a central tracking system in a 2 T superconducting solenoidal magnet, a liquid argon/uranium calorimeter, and a muon spectrometer [8]. The tracking system consists of a silicon microstrip tracker and a scintillating fiber tracker and provides coverage for charged particles in the pseudorapidity range $|\eta| < 3$, where $\eta = -\ln[\tan(\frac{\theta}{2})]$ and θ is the polar angle with respect to the proton beam direction (z). The calorimeters are finely segmented and consist of a central section (CC) covering $|\eta| \leq 1.1$, and two end calorimeters (EC) extending coverage to $|\eta| \approx 4$, all housed in separate cryostats [9]. Scintillators installed between the CC and EC cryostats provide sampling of developing showers for $1.1 < |\eta| < 1.4$. The electromagnetic (EM) section of the calorimeter has four longitudinal layers and transverse segmentation of 0.1×0.1 in $\eta - \phi$ space (where ϕ is the azimuthal angle), except in the third layer, corresponding to EM shower maximum, where it is 0.05×0.05. The data sample was collected between April 2002 and March 2004, using triggers requiring at least one energetic cluster or two less energetic ones in the electromagnetic layers of the calorimeter. The integrated luminosity of the sample is 263 ± 17 pb^{-1}.

Photons and electrons are identified in two steps: first, selection of the EM clusters, and then their separation into photons or electrons. EM clusters are selected from calorimeter clusters by requiring that (i) at least 90% of the energy be deposited in the EM section of the calorimeter, (ii) the calorimeter isolation variable (I) be less than 0.15, where $I = [E_{\rm tot}(0.4) - E_{\rm EM}(0.2)]/E_{\rm EM}(0.2)$, where $E_{\rm tot}(0.4)$ is the total shower energy in a cone of radius $\mathcal{R} = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$, and $E_{\rm EM}(0.2)$ is the EM energy in a cone $\mathcal{R} = 0.2$, (iii) the transverse and longitudinal shower profiles be consistent with those expected for an EM shower, and (iv) the scalar sum of the p_T of all tracks originating from the primary vertex in an annulus of $0.05 < \mathcal{R} < 0.4$ around the cluster be less than 2 GeV. The cluster is then defined as an electron if there is a reconstructed track pointing to it and a photon otherwise. Jets are reconstructed using the iterative, midpoint cone algorithm [10] with a cone size of 0.5. $\not\!\!E_T$ is determined from the energy deposited in the calorimeter for $|\eta| < 4$ and is corrected for jet and EM energy scales.

We select $\gamma\gamma$ candidates by requiring events to have two photons each with $E_T > 20$ GeV and pseudorapidity $|\eta| < 1.1$. To suppress events with mismeasured $\not\!\!E_T$, we apply the following requirements. We reject any event when the difference in azimuth ($\Delta\phi$) between the highest E_T jet (if jets are present) and the direction of the $\not\!\!E_T$ is more than 2.5 rad, or if the $\Delta\phi$ between the direction of the $\not\!\!E_T$ and either photon is less than 0.5 rad. These selections yield 1909 events ($\gamma\gamma$ sample), out of which 1800 have $\not\!\!E_T <$ 15 GeV and two have $\not\!\!E_T > 40$ GeV. The two events constitute the $\gamma\gamma\not\!\!E_T$ sample.

The main backgrounds arise from standard model processes with misidentified photons and/or mismeasured $\not\!\!E_T$. The background from processes with no inherent $\not\!\!E_T$ (multijet events, direct photon production, $Z \rightarrow ee$, etc.) is estimated using events with two EM clusters that satisfy photon-identification criteria (i) and (ii) but fail the shower-shape requirement (iii). These events, called the QCD sample, must pass the same trigger and other selec-

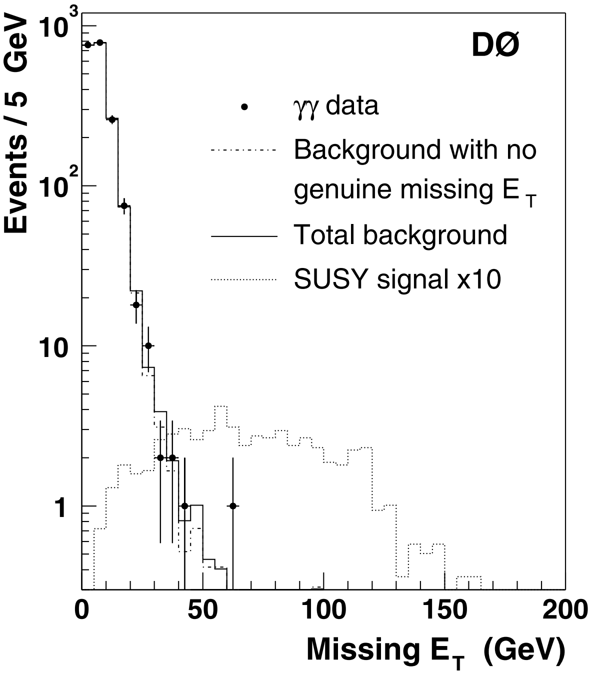

FIG. 1. The $\not{E}_T$ distribution for the diphoton and background samples. Also shown is the expected distribution for the GMSB point with $\Lambda = 80$ TeV, multiplied by a factor of 10.

tions that define the $\gamma\gamma$ sample. They have characteristics similar to the background in the $\gamma\gamma$ sample and, in particular, are expected to have similar $\not{E}_T$ resolution. This assumption was checked by varying the selection criteria and comparing the $\not{E}_T$ distribution in the QCD sample to that in $Z \rightarrow ee$ events. The QCD sample comprises 18 437 events, with 17 379 events having $\not{E}_T < 15$ GeV, and 27 events with $\not{E}_T > 40$ GeV. We estimate the background in the $\gamma\gamma\not{E}_T$ sample resulting from mismeasurement of $\not{E}_T$ by normalizing the number of QCD events to that of the $\gamma\gamma$ sample for $\not{E}_T < 15$ GeV. This yields 2.8 ± 0.5 events with $\not{E}_T > 40$ GeV, with uncertainty dominated by the statistics of the QCD sample.

The other sources of background correspond to events with genuine $\not{E}_T$ in which an electron is misidentified as a photon, for example, from $W +$ "γ" events (where "γ" denotes both true photons and jets misidentified as photons), and from $Z \rightarrow \tau^+\tau^- \rightarrow e^+e^- + X$ and $t\bar{t} \rightarrow e^+e^- +$ jets production. We estimate this contribution using the $e\gamma$ sample which has the same trigger, kinematic, and EM identification requirements as the $\gamma\gamma$ sample. This sample contains 889 events, 782 events with $\not{E}_T < 15$ GeV and 15 events with $\not{E}_T > 40$ GeV. To estimate the contribution of such events to the $\gamma\gamma\not{E}_T$ sample, we first subtract the QCD background component of the $e\gamma$ sample. This is done by normalizing the QCD sample to the $e\gamma$ sample for $\not{E}_T < 15$ GeV. Then, using the probability for an electron to be misidentified as a photon (measured using $Z \rightarrow ee$ events to be 0.064 ± 0.004), we estimate this background to be 0.9 ± 0.2 events with statistically dominated uncertainty. Therefore the total expected background to the $\gamma\gamma\not{E}_T$ sample is 3.7 ± 0.6 events. The $\not{E}_T$ distributions for the $\gamma\gamma$ sample, background without genuine $\not{E}_T$, and the total background are shown in Fig. 1, together with an expected distribution from the Snowmass Slope model with $\Lambda = 80$ TeV, the latter multiplied by a factor of 10 for clarity.

To estimate the expected signal, we generated Monte Carlo (MC) events for several points on the Snowmass Slope (see Table I), covering the neutralino mass range from 72 GeV, somewhat below the existing limits [6,7], to 116 GeV. We used ISAJET 7.58 [11] to determine SUSY interaction eigenstate masses and couplings. PYTHIA 6.202 [12] was used to generate the events after determining the sparticle masses, branching fractions, and leading-order (LO) production cross sections using the CTEQ5L [13] parton distribution functions (PDF). MC events were processed through full detector simulation and reconstruction and processed with the analysis program used for the data.

The dominant contributions to the cross section are from the production of lightest charginos ($\tilde{\chi}_1^+\tilde{\chi}_1^-$) and chargino-second neutralino pairs ($\tilde{\chi}_2^0\tilde{\chi}_1^{\pm}$). The total cross section in Table I is calculated to leading order in PYTHIA for GMSB SUSY production. The "K factor" used to account for higher-order corrections is applied to estimate the next-to-leading-order cross section. The values of the K factor in Table I are taken from Ref. [14]. The sources of error on signal efficiency include uncertainty on photon identifica-

TABLE I. Points on the Snowmass Slope: their cross sections, efficiencies, and cross-section limits.

Λ, TeV	$m_{\tilde{\chi}_1^0}$, GeV	$m_{\tilde{\chi}_1^+}$, GeV	$\sigma_{\rm tot}^{\rm LO}$, pb	K factor	Efficiency	95% C.L. Limit, pb
55	71.8	126.3	0.735	1.236	0.092 ± 0.009	0.184
60	79.1	140.2	0.468	1.227	0.100 ± 0.009	0.170
65	86.4	154.3	0.301	1.217	0.111 ± 0.011	0.153
70	93.7	168.2	0.204	1.207	0.124 ± 0.012	0.137
75	101.0	182.3	0.138	1.197	0.137 ± 0.013	0.124
80	108.2	196.0	0.094	1.187	0.149 ± 0.014	0.114
85	115.5	209.9	0.066	1.177	0.154 ± 0.015	0.110

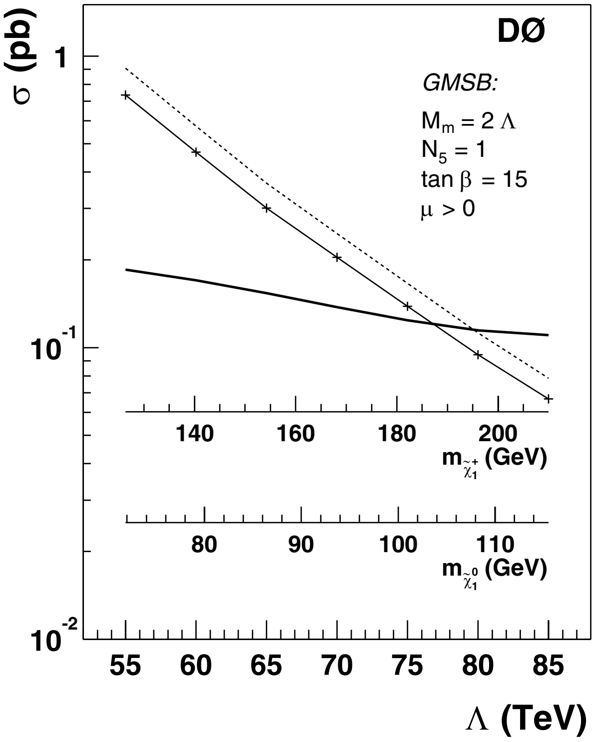

FIG. 2. Predicted cross sections for the Snowmass Slope model vs Λ in leading order (thin solid line with crosses), multiplied by the K factor (thin dashed line), and the 95% C.L. limits (solid line).

tion (4% per photon), MC statistics (5%), and choice of PDF (5%).

Since the observed number of events is in good agreement with that expected from the standard model, we conclude that there is no evidence for GMSB SUSY in our data. To calculate the upper limit on the production cross section for each sampled point on the Snowmass Slope, we use a Bayesian approach [15] with a flat prior for the signal cross section. The calculation takes into account uncertainties on the expected number of background events, efficiency, and luminosity. The selection $\not{E}_T > 40$ GeV for the signal sample leads to the best expected limit, given the predicted background and expected signal distributions. Our limits are shown in Table I, and plotted in Fig. 2, together with the expected signal cross section. The upper limit on the cross section is below the expected value for $\Lambda < 79.6$ TeV, corresponding to lower limits on gaugino masses of $m_{\tilde{\chi}_1^+} > 194.9$ GeV and $m_{\tilde{\chi}_1^0} > 107.7$ GeV. The expected limit, given the predicted number of background events, is $\Lambda < 74.5$ TeV. We find that the gaugino mass limits depend only slightly on the parameters of the minimal GMSB. We have considered models with values of tanβ and N_5 different from the Snowmass Slope and arrive at very similar results as detailed by Table II.

TABLE II. Limits on the Snowmass Slope and two other GMSB models.

Fixed parameters				95% C.L. lower limits			
M_m/Λ	tanβ	N_5	sgn(μ)	Λ	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_1^+}$	$m_{\tilde{\chi}_2^0}$
2	15	1	+	79.6	107.7	194.9	195.9
2	5	1	+	79.5	106.0	191.6	193.3
10	5	2	+	44.0	111.4	196.0	198.7

To summarize, we searched for inclusive high-E_T diphoton events with large missing transverse energy. Such events are predicted in supersymmetric models with low-scale gauge-mediated supersymmetry breaking. We find no excess of such events and interpret the result as a lower limit on gaugino masses. For a representative point in the parameter space, we determine that at a 95% confidence level, the masses of the lightest chargino and neutralino are larger than 195 and 108 GeV, respectively. These are the most restrictive limits to date for the Snowmass Slope model.

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