Experimental Search for Chargino and Neutralino Production in Supersymmetry Models with a Light Gravitino

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We search for inclusive high E_T diphoton events with large missing transverse energy in $p\bar{p}$ collisions at $\sqrt{s}$=1.8 TeV. Such events are expected from pair production of charginos and neutralinos within the framework of the minimal supersymmetric standard model with a light gravitino. No excess of events is observed. In that model, and assuming gaugino mass unification at the GUT scale, we obtain a 95% CL exclusion region in the supersymmetry parameter space and lower mass bounds of 150 GeV/c^2 for the lightest chargino and 77 GeV/c^2 for the lightest neutralino.

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Supersymmetric models with a light gravitino ($\tilde{G}$), first proposed by Fayet [1], have generated recent theoretical interest [2–4]. These models are characterized by a supersymmetry breaking scale Λ as low as 100 TeV and a gravitino which is naturally the lightest supersymmetric particle (LSP). The lightest superpartner of a standard model particle, assumed here and in most analyses to be the lightest neutralino ($\tilde{\chi}_1^0$), is the next-to-lightest supersymmetric particle (NLSP). If $\tilde{\chi}_1^0$ has a non-zero photino component, it is unstable and decays into a photon plus a gravitino ($\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$).

In this Letter, we present a direct search for supersymmetry with a light gravitino in the framework of the minimal supersymmetric standard model (MSSM). In this framework the gaugino-Higgsino sector (excluding gluinos) is described by four parameters: M_1, M_2, μ, and $\tan\beta$, where M_1 and M_2 are the $U(1)$ and $SU(2)$ gaugino mass parameters, μ is the Higgsino mass parameter, and $\tan\beta$ is the ratio of the vacuum expectation values of the two Higgs doublets [5]. With the assumption of gaugino mass unification at the GUT scale, $M_1 = \frac{5}{3}M_2\tan^2\theta_W$, where θ_W is the weak mixing angle. There are four neutralinos ($\tilde{\chi}_i^0,\ i = 1,2,3,4$) and two charginos ($\tilde{\chi}_j^\pm,\ j = 1,2$) whose masses and couplings are fixed by M_2, μ and $\tan\beta$. We assume $\tan\beta > 1$ in this analysis.

ΛWe search for neutralino and chargino pair production in $\sqrt{s}$=1.8 TeV $p\bar{p}$ collisions at the Fermilab Tevatron. The $\tilde{\chi}_1^0$ is assumed to be short-lived, decaying within the detector to $\gamma\tilde{G}$ with a branching ratio of 100%, as is expected if the gravitino is sufficiently light and the photino component of the $\tilde{\chi}_1^0$ is non-zero [6]. Decay to a Higgs boson is assumed to be kinematically inaccessible. R-parity conservation is assumed so that supersymmetric particles are pair produced and the LSP is stable and non–interacting. Thus pair production of charginos and neutralinos yields $\gamma\gamma\not{E}_T$ events with high transverse energy (E_T) photons and large missing transverse energy ($\not{E}_T$), with or without jets.

Recently DØ reported a search [7] for $\gamma\gamma\not{E}_T$ events based on supersymmetry models with $\tilde{\chi}_1^0$ as the LSP. In this analysis, we present the first experimental study of $p\bar{p} \rightarrow \gamma\gamma\not{E}_T + X$ based on the MSSM with a light gravitino as the LSP.

The data used in this analysis were collected with the DØ detector during the 1992–1996 Tevatron run at $\sqrt{s}$=1.8 TeV and represent an integrated luminosity of 106.3 ± 5.6 pb^{-1}. A detailed description of the DØ detector can be found in Ref. [8]. The trigger requires one electromagnetic (EM) cluster with transverse energy $E_T > 15$ GeV, one jet with $E_T > 10$ GeV, and $\not{E}_T > 14$ GeV ($\not{E}_T > 10$ GeV for about 10% of the data taken early in the Tevatron run). The jets in the trigger include non-leading EM clusters. Photons are identified through a two-step process: the selection of isolated EM energy clusters and the rejection of electrons. The EM clusters are selected from calorimeter energy clusters by requiring (i) at least 95% of the energy to be deposited in the EM section of the calorimeter, (ii) the transverse and longitudinal shower profiles to be consistent with those expected for an EM shower, and (iii) the energy in an annular isolation cone from radius 0.2 to 0.4 around the cluster in $\eta - \phi$ space to be less than 10% of the cluster energy, where η and ϕ are the pseudorapidity and azimuthal angle. Electrons are removed by rejecting EM 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. $\not{E}_T$ is determined from the energy deposition in the calorimeter for $|\eta| < 4.5$.

To be selected as $\gamma\gamma\not{E}_T$ candidates, events are first required to have two identified photons, one with $E_T^{\gamma_1} >$ 20 GeV and the other with $E_T^{\gamma_2} > 12$ GeV, each with pseudorapidity $|\eta^\gamma| < 1.2$ or $1.5 < |\eta^\gamma| < 2.0$, the regions with good photon identification. We denote the 28 events passing these photon requirements as the $\gamma\gamma$ sample. We then require $\not{E}_T > 25$ GeV with at least one reconstructed vertex in the event to ensure good measurement of $\not{E}_T$. No requirement on jets is made. Two events satisfy all requirements.

The principal backgrounds are multijet, direct photon, $W + \gamma$, $W +$ jets, $Z \rightarrow ee$, and $Z \rightarrow \tau\tau \rightarrow ee$ events from Standard Model processes with misidentified photons and/or mismeasured $\not{E}_T$. The background due to $\not{E}_T$ mismeasurement is estimated using events with two EM-like clusters which satisfy looser EM cluster requirements than those discussed above, and for which at least one of the two fails the EM shower profile consistency requirement (ii) above. In addition, these events must pass the photon kinematic requirements. These events, called the QCD sample, are similar to those of the $\gamma\gamma$ sample and are expected to have similar $\not{E}_T$ resolution. By normalizing the number of events with $\not{E}_T < 20$ GeV in the QCD sample to that in the $\gamma\gamma$ sample, we obtain a background of 2.1 ± 0.9 events due to $\not{E}_T$ mismeasurement for $\not{E}_T > 25$ GeV.

Other backgrounds are due to events with genuine $\not{E}_T$ such as those from W+'γ' (where 'γ' can be a real or a fake photon), $Z \rightarrow \tau\tau \rightarrow ee$, and $t\bar{t} \rightarrow ee +$jets production. These events would fake $\gamma\gamma\not{E}_T$ events if the electrons were misidentified as photons. We estimate their contribution using a sample of e'γ' events passing the kinematic requirements, including that on $\not{E}_T$. Electrons are selected from the identified EM clusters with matched tracks. Taking into account the probability (0.0045 ± 0.0008, determined from $Z \rightarrow ee$ data) that an electron is misidentified as a photon, we estimate a background of 0.2 ± 0.1 events. Adding the two background contributions together yields 2.3 ± 0.9 events. The $\not{E}_T$ distributions of the $\gamma\gamma$ sample and the background sample are compared in Fig. 1.

Chargino and neutralino pair production and decay are

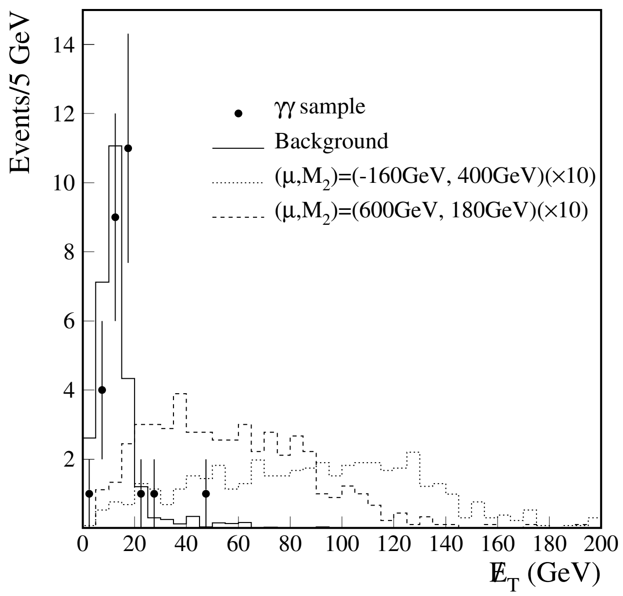

FIG. 1. The $\not\!\!E_T$ distributions of the $\gamma\gamma$ and background samples. The number of events with $\not\!\!E_T < 20$ GeV in the background sample is normalized to that in the $\gamma\gamma$ sample. Also shown are the expected distributions (multiplied by 10) from two representative points in the supersymmetry parameter space, with $\tan\beta = 2$.

modeled using the SPYTHIA program [9], a supersymmetric extension of the PYTHIA 5.7 program [10]. Squarks and sleptons are assumed to be heavy. This assumption is conservative because light sleptons would lead to events with less jet activity and would therefore improve detection efficiency. For light squarks, no change in efficiency is expected. To explore the parameter space, we choose to work in the (μ, M_2) plane while keeping $\tan\beta$ fixed. We generate $\tilde{\chi}_i^0\tilde{\chi}_j^0$, $\tilde{\chi}_i^0\tilde{\chi}_j^\pm$ and $\tilde{\chi}_i^\pm\tilde{\chi}_j^\pm$ events for a large number of points in the (μ, M_2) parameter space. Table I shows the resulting theoretical cross sections σ_{th} for several representative points, calculated using the CTEQ3L parton distribution function [11]. If CTEQ3M parton distributions were used, σ_{th} would change by $\sim 5\%$. To determine the signal efficiencies, Monte Carlo events are run through a GEANT [12] based DØ detector simulation program, a trigger simulator, and the same trigger requirements, reconstruction, and analysis as the data. The total signal efficiency ϵ (including efficiencies of the trigger, reconstruction, photon identification, and kinematic requirements) varies greatly, from $\sim 0.01\%$ to $\sim 26\%$, depending largely on the masses of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ and their mass difference. The estimated systematic error on the total efficiency is 0.06ϵ, dominated by uncertainties in photon identification efficiency (0.04ϵ) and Monte Carlo simulation (0.03ϵ).

With two events observed and 2.3 ± 0.9 events expected from background, we observe no excess of events. We compute 95% CL upper limits on the cross section σ for

μ	M_2	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_1^\pm}$	σ_{th}	Efficiencies (%)		Limits (pb)	
GeV	GeV	GeV/c^2		(pb)	ϵ	ϵ_D	σ	σ_D
-160	300	143.9	167.8	0.12	26.0±1.4	36.4	0.18	0.13
-600	140	72.5	146.4	0.36	17.2±1.2	32.1	0.28	0.15
-800	165	84.7	170.0	0.20	15.1±1.1	26.4	0.32	0.18
200	300	118.1	160.2	0.15	21.3±1.3	31.9	0.23	0.15
400	190	89.4	166.4	0.19	20.1±1.3	32.5	0.24	0.15
800	170	83.2	161.6	0.25	19.6±1.3	33.4	0.25	0.14

TABLE I. Representative points in the (μ, M_2) plane for $\tan\beta = 2$ with GEANT simulation. These points are chosen to be near our 95% CL bounds, where the experimental 95% CL cross section σ equals the theoretical cross section σ_{th}. The efficiency ϵ is for observing the total cross section σ, fiwhile ϵ_D and σ_D are the efficiency and cross section for observing the detectable events, those which satisfy the kinematic cuts $E_T^{\gamma_1} > 20$ GeV, $E_T^{\gamma_2} > 12$ GeV, $|\eta^\gamma| < 1.2$ or $1.5 < |\eta^\gamma| < 2.0$, and $\not\!\!E_T > 25$ GeV at the generator level. The total efficiency $\epsilon = \epsilon_D \times \epsilon_K$ where ϵ_K is the efficiency of the kinematic cuts.

the Monte Carlo sampled points in the (μ, M_2) plane using a Bayesian approach [13] with a flat prior distribution for the signal cross section. The calculation takes into account the errors on the luminosity, the efficiency, and the number of background events. Depending on the values of the supersymmetry parameters, the 95% CL upper limits on the total cross section vary widely from several hundred pb for light charginos/neutralinos to $\sigma \sim 0.18$ pb for heavy charginos/neutralinos.

To derive bounds in the (μ, M_2) plane, the values of μ and M_2 are varied around the sampled points until the theoretical cross sections σ_{th} exceed the upper limits σ. The interpolated bounds in the (μ, M_2) plane are shown in Fig. 2 for $\tan\beta = 1.05, 2, 100$. The regions below the lines are excluded by this analysis. The bounds depend on the value of $\tan\beta$ slightly, becoming stronger in the $\mu < 0$ half-plane and weaker in the other half-plane as $\tan\beta$ is increased. Our limits are valid for $|\mu| > 10$ GeV and $M_2 > 10$ GeV; small $|\mu|$ and M_2 are excluded by LEP I [14].

Figure 3 compares the bounds in the (μ, M_2) plane for $\tan\beta = 2$ with those estimated from LEP data [3] within the framework of a light gravitino where they assume a 75 GeV/c^2 selectron for t-channel exchange. Individual LEP experiments [15] have recently studied light gravitino models, but their bounds are weaker than those estimated in Ref. [3], which combined preliminary results from all four LEP experiments. Our bounds exclude the region of parameter space suggested in Ref. [3] for the chargino interpretation of an event candidate shown by the CDF Collaboration [16]. Also shown are the contours of constant mass for $m_{\tilde{\chi}_1^\pm} = 150$ GeV/c^2 and $m_{\tilde{\chi}_1^0} = 77$ GeV/c^2. Since these are the largest masses for which the mass contours lie entirely in the excluded region, we obtain 95% CL lower mass limits of 150 GeV/c^2 for the lightest chargino and 77 GeV/c^2 for the lightest neutralino. These limits are also valid for larger M_2 and $|\mu|$ values than shown in Fig. 3. This

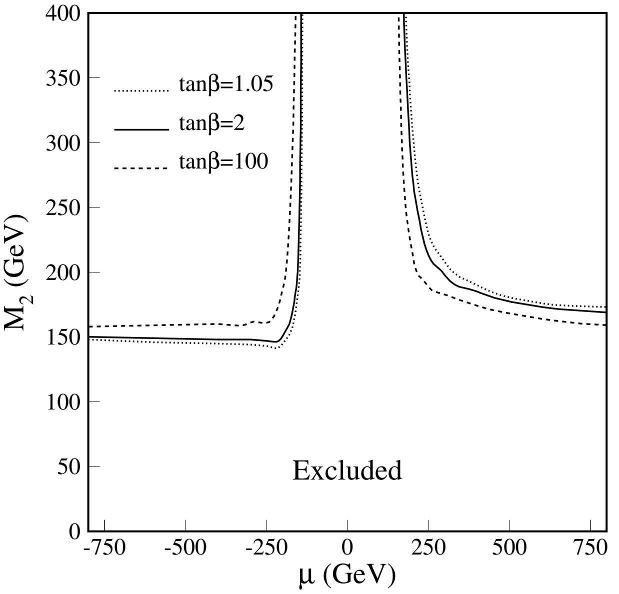

FIG. 2. 95% CL bounds in the (μ, M_2) plane for $\tan\beta = 2$ (solid line), $\tan\beta = 1.05$ (dotted line), and $\tan\beta = 100$ (dashed line).

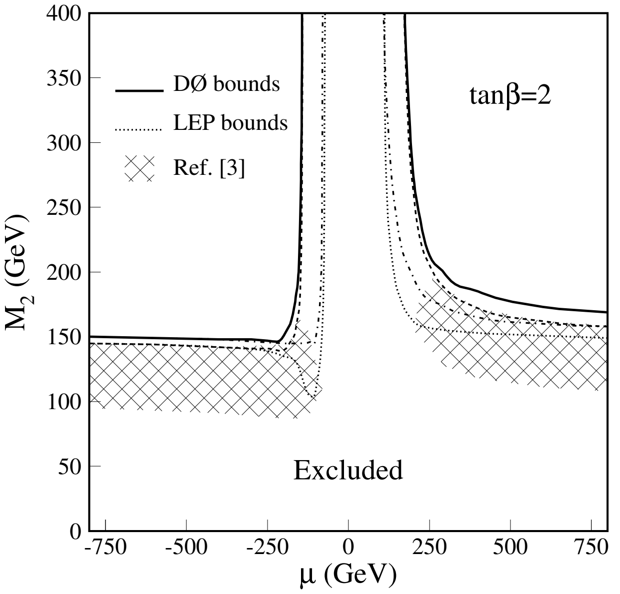

FIG. 3. Bounds in the (μ, M_2) plane for $\tan\beta = 2$. The region below the two solid lines is excluded at 95% CL. Also shown are the bounds estimated in Ref. [3] from LEP data (dotted line) and the contours of constant $m_{\tilde{\chi}_1^\pm} = 150$ GeV/c^2 (dashed line) and $m_{\tilde{\chi}_1^0} = 77$ GeV/c^2 (dot-dashed line). The hatched areas are suggested in Ref. [3] for the chargino interpretation of the CDF event candidate in the model.

77 GeV/c^2 lower mass limit also rules out a large part of the parameter space suggested for the selectron interpretation of the CDF event candidate in the model, as discussed in Ref. [3]. These mass limits are insensitive to the choice of $\tan\beta$, varying less than 2 GeV/c^2 over the range $1.05 < \tan\beta < 100$, as long as our assumption that $\tilde{\chi}_1^0$ is the NLSP is satisfied. For large $\tan\beta$ values, this assumption may not be satisfied [4].

Most of the theoretical cross section for the $\gamma\gamma\not\!\!E_T$ process is due to $\tilde{\chi}_1^\mp\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ production. For the large part of the parameter space with $|\mu| \gg M_2$, the relation $m_{\tilde{\chi}_1^\pm} \approx m_{\tilde{\chi}_2^0} \approx 2 \times m_{\tilde{\chi}_1^0}$ holds, so we can express our cross section limits simply in terms of $m_{\tilde{\chi}_1^\pm}$. Figure 4 shows the 95% CL upper limits for both processes, together with the theoretical predictions for $\tan\beta = 2$ and $\mu = -500$ GeV. The experimental limits are insensitive to the choice of $\tan\beta$ and μ while the theoretical cross section varies by about 10%. Our data rule out chargino masses below ≈ 137 GeV/c^2 in models with a light gravitino, assuming $|\mu| \gg M_2$. This limit, though weaker than the 150 GeV/c^2 limit determined above from all processes contributing to $\gamma\gamma\not\!\!E_T$ final states, is useful for comparison with semi-exclusive calculations of gaugino production.

In summary, we have searched for inclusive high E_T diphoton events with large missing transverse energy. Such events are expected in the framework of supersymmetric models with a light gravitino. No excess of events is found. The null result, interpreted in this framework assuming gaugino mass unification at the GUT scale, $B(\tilde{\chi}_1^0 \to \gamma\tilde{G}) = 100\%$, and a short-lived NLSP $\tilde{\chi}_1^0$, yields 95% CL lower mass limits of 150 GeV/c^2 for the lightest

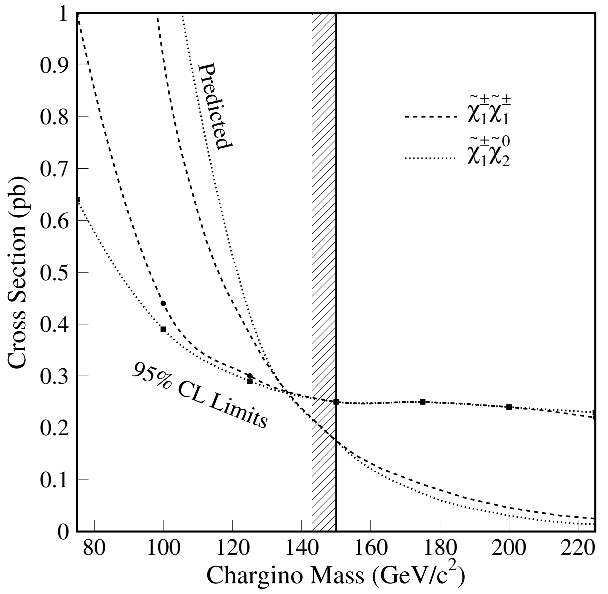

FIG. 4. Measured 95% CL upper limits and predicted theoretical cross sections for $\tilde{\chi}_1^\mp\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ production as a function of $m_{\tilde{\chi}_1^\pm}$, assuming $m_{\tilde{\chi}_1^\pm} \approx m_{\tilde{\chi}_2^0} \approx 2 \times m_{\tilde{\chi}_1^0}$. The vertical hatched line is the 95% CL lower limit on $m_{\tilde{\chi}_1^\pm}$ determined using the total cross section for all chargino/neutralino pair production, as determined in this paper.

chargino and 77 GeV/c^2 for the lightest neutralino.

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