Fermi National Accelerator Laboratory

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CDF

Search for Radiative Decays of Neutralinos in Proton-Antiproton Collisions at $\sqrt{s} = 1.8$ TeV

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Abstract

In a search for supersymmetric signatures, we have sought evidence for the radiative decay of neutralinos produced in proton-antiproton collisions at $\sqrt{s} = 1.8$ TeV in the 1988-1989 run with integrated luminosity 4.3 pb^{-1}. Events in the CDF detector containing two photons plus large missing transverse energy were investigated. The observed event rate and the missing transverse energy distribution of the two-photon events are consistent with QCD predictions. Inferred limits on squark and gluino masses that take into account effects of possible cascade decays depend on parameters of the SUSY model. The particular choices $\mu = -40$ GeV/c^2 and $\tan\beta = 1.5$ lead to 90% confidence-level asymptotic lower limits of 110 GeV/c^2 and 240 GeV/c^2 for squarks and gluinos respectively.

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Squarks ($\tilde{q}$) and gluinos ($\tilde{g}$) are the supersymmetry (SUSY) partners of quarks and gluons. If they exist they would be the most copiously produced SUSY particles at hadron colliders. R-parity conservation requires SUSY particles that result from interactions of ordinary matter to be produced in pairs. Squarks and gluinos decay into charginos and neutralinos through decay chains that continue until the lightest supersymmetric particle (LSP) is reached. R-parity conservation implies the LSP is stable and interacts weakly with matter. The LSP thus, typically, deposits little energy in detection apparatus and results in apparent substantial missing energy in detected events. The LSP is likely to be electrically neutral and is expected to be a neutralino. Neutralinos are mixtures of the fermionic partners of the neutral gauge and Higgs bosons. In the minimal supersymmetric standard model (MSSM) [1], the mass-eigenstate physical neutralinos χ_i (i=1...4) are linear combinations of four neutralino components, the photino ($\tilde{\gamma}$), the zino ($\tilde{Z}$) and the two higgsinos ($\tilde{H}_1^0$, $\tilde{H}_2^0$). With the χ_i's labeled in order of increasing mass, χ_1 should be the LSP. Analyses of recent data on e^+e^- interactions obtained at LEP and at SLC [2] suggest that the mass of the LSP is heavier than 10 - 20 GeV/c^2 [3]. The masses and mixing of neutralino components are determined by as yet unknown SUSY parameters [4]. Calculations show that the fraction of neutralino radiative decays, $\chi_j \rightarrow \chi_i$ (j>i)γ can be appreciable in some cases [5], [6]. These include: (a) the neutralinos are almost pure photino, or pure higgsino, states, and the higgsino-like state is either the first or the second lightest neutralino, and (b) both the higgsino-like neutralinos are close in mass [6], [7]. In these cases, the competitive fermion-pair ($f\bar{f}$) processes $\chi_j \rightarrow f\bar{f}\chi_i$ are expected to be suppressed.

We searched for events with radiative decays of neutralinos. Since the parent particles are produced in pairs we expect that some of the final states will contain two photons as well as substantial missing transverse energy ($\not{E}_T$). In the analysis, we took into account the following processes: $\tilde{g} \rightarrow q\bar{q}\chi_2 \rightarrow q\bar{q}\chi_1\gamma$, $\tilde{q} \rightarrow q\tilde{g} \rightarrow qq\bar{q}\chi_2 \rightarrow qq\bar{q}\chi_1\gamma$ for $m(\tilde{q}) > m(\tilde{g})$, and $\tilde{g} \rightarrow \bar{q}\tilde{q} \rightarrow q\bar{q}\chi_2 \rightarrow q\bar{q}\chi_1\gamma$, $\tilde{q} \rightarrow q\chi_2 \rightarrow q\chi_1\gamma$ for $m(\tilde{q}) < m(\tilde{g})$. The effect of additional cascade and radiative decays is discussed later for one representative choice of SUSY parameters.

We searched for such signals in a data sample produced with an integrated luminosity of 4.3 pb^{-1} of proton-antiproton collisions at $\sqrt{s}$ = 1.8 TeV accumulated with the Collider Detector at Fermilab (CDF) during the 1988 -1989 run at the Tevatron. A previously reported [8] search found no evidence for SUSY particles among events in CDF with ≥2 jets plus missing E_T. In the absense of cascade decays, asymptotic lower limits on mass were set at 126 GeV/c^2 for squarks and 141 GeV/c^2 for gluinos.

For the analysis discussed here the most important components of the CDF detector are the assemblies of projective electromagnetic (EM) and hadron (HAD) calorimeter towers cylindrically arrayed around the drift-chamber tracker and the proportional chambers (CES) embedded in the EM calorimetry at a position near shower maximum. Details have been presented elsewhere [9], [10]. This analysis is based on 7.4×10^4 recorded events which satisfied a "diphoton" trigger requirement that there be two or more electromagnetic (EM) calorimeter clusters each with E_T (EM) > 10 GeV. Events were selected which had two or more clusters each with E_T(EM) > 10 GeV deposited in EM cells and both in the pseudorapidity ($\eta = -\ln(\tan \theta/2)$, where θ is the angle between the shower direction and the incident-proton direction) range $|\eta| < 0.9$. Furthermore, the ratio of HAD to EM energy in a cluster, HAD/EM, had to be less than 0.055 + 0.045× E(GeV)/100, where E(GeV) is the cluster energy in GeV. In addition, we required the lateral energy sharing between calorimeter towers [11] to be consistent with that of electron showers which originate from the interaction point. This constraint eliminated cosmic-ray showers and multi-vertex events - 17796 events passed. Further selection criteria applied to this event sample are that (1) no track point toward an EM shower - 5617 events survived; (2) the fraction of the energy recorded in EM calorimeter towers at the borders of the photon cluster be less than one-tenth the cluster energy - 857 events survived; (3) a comparison of the shower profile in the CES with that of a calibration photon-shower shape [11] yield $\chi^2 < 20$; (4) the EM shower be inside the fiducial volume restricted by the sensitive area of the CES; (5) the highest-E_T cluster be less than 35 GeV, in order to separate single photons from π^0-decay photon pairs which at this energy have comparable profile χ^2 values - 149 events survived. Since the trigger efficiency becomes nearly 100% at E_T(EM) > 13 GeV, as will be described below, we kept only events with 13 GeV < E_T(EM) < 35 GeV. Sixty events remained as SUSY-particle production candidates.

In this sample the major backgrounds to possible SUSY-particle radiative decay photons are single or multiple neutral jets that contain neutral mesons, π^0, η etc. (hereafter generically abbreviated as π^0) and directly produced single photons and photon pairs. The separation between photons and neutral jets was made statistically by requiring that the transverse shower profile of an EM shower at the CES pass a goodness-of-fit χ^2 test. The calculated fraction of the 60 selected neutral-jet events that are $\gamma\gamma$ events is 37 ± 19 % [10].

The trigger efficiency was determined from a study of electron pairs primarily produced in Drell-Yan processes. This showed that the diphoton trigger, whose threshold is E_T = 10 GeV, becomes fully efficient at $E_T \geq$ 13 GeV [10]. The geometrical and kinematic acceptances were determined from a study of simulated events generated by the PAPAGENO [12] Monte Carlo program. The efficiencies for the cuts on photon-selection were obtained from study of detected W-decay electrons.

The distribution in missing E_T, the most important indicator of SUSY production, is shown in Fig. 1(a) for the 60 SUSY candidate events passing our selection cuts. The resolution in missing E_T, studied with minimum-bias triggered events, is $[0.47\times\Sigma E_T]^{1/2}$ (GeV), where ΣE_T is the scalar sum of E_T deposited in the calorimeters. Shown in the Fig. 1(a) inset is the distribution of missing-E_T "significance", $S = E_T(\text{miss})/\sqrt{\Sigma E_T}$. The dotted histograms in Fig. 1(a) show, in the absence of a SUSY signal, the expected distributions for events with two photons produced in QCD processes, as predicted by the PAPAGENO Monte Carlo program supplemented with a full simulation of the CDF detector response. We see that the observed distributions are indistinguishable from the QCD expectations. The agreement of the prediction with the observed S distribution also gives us confidence in our ability to correctly model the missing-E_T resolution of the detector. We observe no events with more than 21 GeV missing E_T in the data. (For contrast, see Fig. 1(b) for a typical SUSY case described below.) This agreement with the QCD expectation implies that there is no significant excess of events that can be attributed to SUSY-particle production.

Our limits on SUSY production are based on the observation that no events that pass our selection requirements have missing-E_T greater than 25 GeV, account having been taken of the missing-E_T measurement resolution. As a function of $m(\tilde{q})$ and $m(\tilde{g})$, we have evaluated $\tilde{g}\tilde{g}$, $\tilde{q}\bar{\tilde{q}}$ and $\tilde{g}\tilde{q}$ production cross-sections and selection efficiencies, and calculated the expected number of SUSY events with missing-E_T greater than 25 GeV that would be accepted. This calculation also used the PAPAGENO Monte Carlo event generator program [12] with MRSB structure functions [13], and $Q^2 = P_T^2/2$ together with the CDF detector-response simulation. Masses of squarks were taken to be degenerate.

To set limits on the squark and gluino masses, we first considered the masses $m(\chi_2) = 40$ GeV/c^2 and $m(\chi_1) = 10$ GeV/c^2. The cut efficiencies for simulated SUSY double photon events are typically 17% for the photon E_T, 36% for the η, and 45% for the missing E_T requirements. Figure 1(b) shows a typical predicted missing E_T distribution, for the case that $m(\tilde{q}) = 110$ GeV/c^2 and $m(\tilde{g}) = 120$ GeV/c^2. The number of entries in Fig. 1(b) is just the number of events that would be detected, having been produced in 4.3 pb^{-1} integrated-luminosity collisions. (Note that corrections for cascade decays and the radiative branching ratio have not as yet been applied.) The solid curves in Fig. 2 show the 90% confidence-level (C.L.) contours in the $(m(\tilde{q})$-$m(\tilde{g}))$ plane for $m(\chi_2) = 40$ GeV/c^2 and $m(\chi_1) = 10$ GeV/c^2. The arrows marked (a) indicate asymptotic limits on the squarks and gluino masses, 126 GeV/c^2 and 153 GeV/c^2 respectively, for this case. When $m(\chi_2)$ varies from 20 GeV/c^2 to 60 GeV/c^2 and $m(\chi_1)$ from 10 GeV/c^2 to 50 GeV/c^2 the squark mass limits lie between 126 GeV/c^2 and 138 GeV/c^2 and the gluino mass limits between 150 GeV/c^2 and 165 GeV/c^2.

This evaluation of the 90%-C.L. limit includes the effect of the systematic uncertainties which result from a combination of the following three sources: (1) 7% uncertainty in the luminosity, (2) 21% uncertainty in the missing E_T cut efficiency due to an 8% uncertainty in the jet-energy correction for non-linear calorimeter response, energy deposition in cracks, jet fragmentation and underlying event energy, and (3) 6% uncertainty in the photon E_T cut efficiency due to a smearing effect of the intrinsic transverse momentum of the initial parton. The uncertainty is 16% in the predicted cross section due to the choice of Q^2 scale within the MRSB structure functions [13]. The total uncertainty in the expected number of events, including the statistical error in the simulation, - about ±32% - corresponds to an uncertainty of a few GeV/c^2 in the mass limits.

The bounds stated above are reduced when account is taken of the branching fractions of the possible cascade decays of squarks and gluinos to χ_2 and radiative decays of χ_2. Both fractional rates depend on SUSY parameters and can be determined definitely within the framework of the MSSM only when the parameters are fixed. We first chose a representative set of the two parameters μ and v_2/v_1 (the mass-mixing term and the ratio of vacuum expectation values) μ = - 40 GeV/c^2, and v_2/v_1 (= tan β) = 1.5. The corresponding region in ($m(\tilde{q})$-$m(\tilde{g})$) space is partly excluded by the ALEPH experiment [3] but only if chargino masses are greater than 45 GeV/c^2. In estimating the branching fraction of cascade decays of the squarks and gluino to χ_2, contributions of left-handed and right-handed squarks were taken separately [14]. In this exemplary case decay to the CP-even Higgs scalar h^0, the mode $\chi_2 \rightarrow \chi_1 h^0$, is not kinematically allowed. Were it allowed, the branching ratio of $\chi_2 \rightarrow \chi_1 \gamma$ [15] would be suppressed. In the calculations a top quark mass of 150 GeV/c^2 and a charged Higgs mass of 500 GeV/c^2 were assumed.

In Fig. 2, the dashed curves indicate the reduced bounds. No limits can be set in the shaded area in Fig. 2 because one or both of the branching fractions are small. The asymptotic limits on the squark and gluino masses, 110 GeV/c^2 and 140 GeV/c^2 respectively, are shown in Fig. 2 with arrows marked (b). The asymptotic mass limits that result from other choices of parameters are shown in Table I. In the absence of any argument in favor of a choice of parameters, experiment at best yields a substantial range of values of lower limits on the masses of squarks and gluino.

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Table I. Asymptotic 90% Confidence-Level limits on squark and gluino masses for six different sets of values of SUSY parameters μ and tan β. (NL) means that no limit can be set.

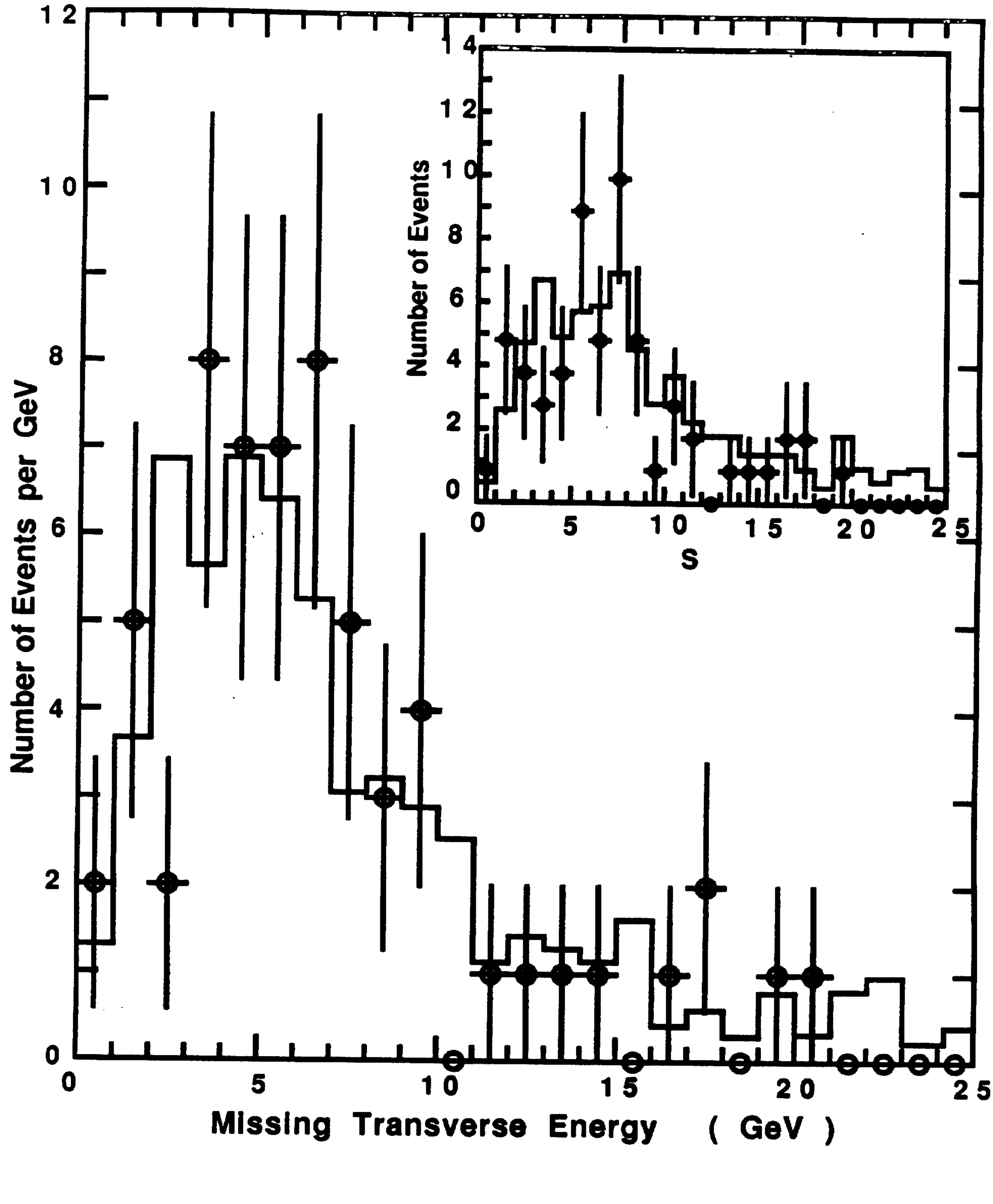
	tan β = 1.5	tanβ = 4.0
μ = - 40 GeV/c^2	m($\tilde{q}$) = 110 GeV/c^2	m($\tilde{q}$) = (NL)
	m($\tilde{g}$) = 140 GeV/c^2	m($\tilde{g}$) = 113 GeV/c^2
μ = - 60 GeV/c^2	m($\tilde{q}$) = (NL)	m($\tilde{q}$) = (NL)
	m($\tilde{g}$) = 105 GeV/c^2	m($\tilde{g}$) = 97 GeV/c^2
μ = - 80 GeV/c^2	m($\tilde{q}$) = (NL)	m($\tilde{q}$) = (NL)
	m($\tilde{g}$) = (NL)	m($\tilde{g}$) = 78 GeV/c^2

Figure Captions

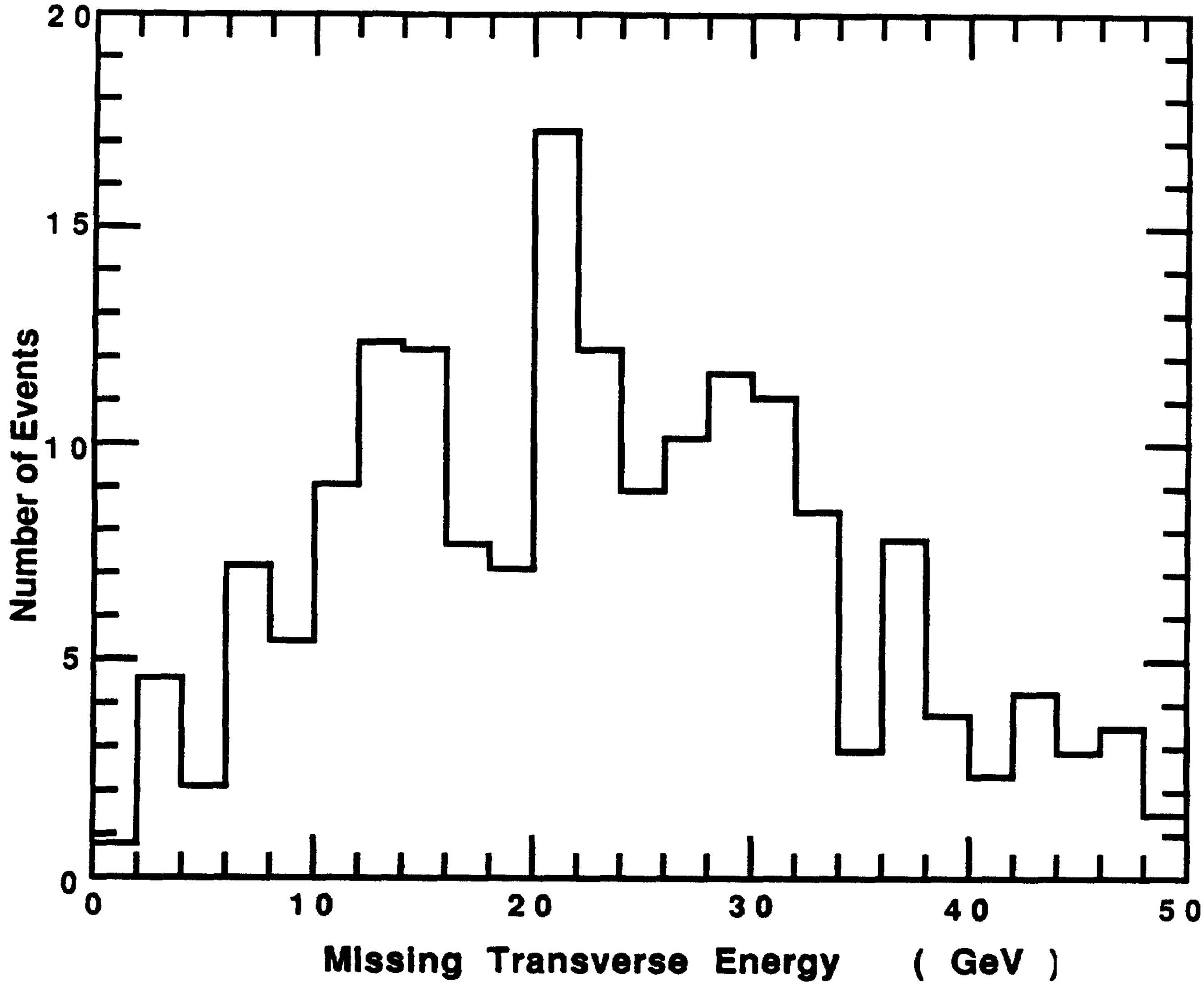
Fig. 1 (a) The observed missing E_T distribution of the 60 SUSY event candidates with 13 GeV< E_T < 35 GeV and $|\eta| < 0.9$ (see text). The indicated uncertainties are statistical only. In the absence of a SUSY signal, the histogram shows a QCD parton shower Monte Carlo prediction for the expected shape of the missing-E_T distribution after the finite experimental resolution has been simulated. Inset: the distribution of missing E_T significance (S, as defined in text) for the above 60 events.

(b) The simulated missing E_T distribution for SUSY two-photon events generated by the PAPAGENO Monte Carlo program [13] for the case that $m(\tilde{q})$ = 110 GeV/c^2 and $m(\tilde{g})$ = 120 GeV/c^2, $m(\chi_2)$ = 40 GeV/c^2 and $m(\chi_1)$ = 10 GeV/c^2. The same luminosity and cuts were applied to the simulated and experimental data.

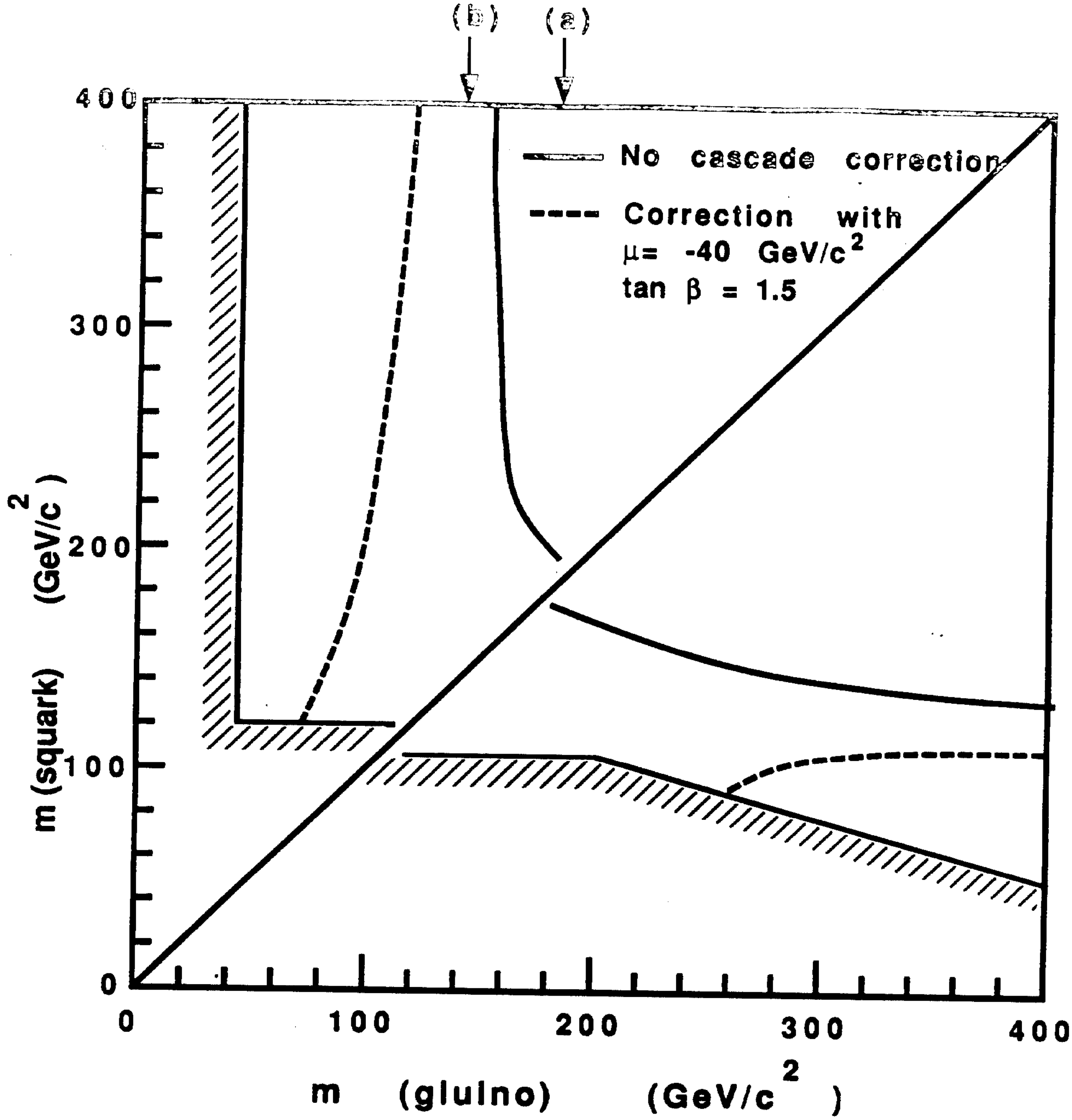
Fig. 2 Mass limits on $m(\tilde{g})$ vs. $m(\tilde{q})$ at the 90 % C.L. for the case that $m(\chi_2)$= 40 GeV/c^2 and $m(\chi_1)$ = 10 GeV/c^2. The solid contour lines are the limits without correction for cascade-decay branching fractions. The dashed contour lines are the reduced limits obtained when those corrections are applied for the case that SUSY parameters μ= - 40 GeV/c^2 and tan β = 1.5. The arrows marked (a) and (b) indicate asymptotic limits. No limits can be set below the shaded line.



Number of Events per GeV
Missing Transverse Energy (GeV)
Number of Events
S



20
15
10
5
0
Number of Events
0
10
20
30
40
50
Missing Transverse Energy (GeV)


(b)
(a)
No cascade correction
Correction with
μ= -40 GeV/c²
tan β = 1.5
0
100
200
300
400
m (squark) (GeV/c²)
m (gluino) (GeV/c²)