Mass and Lifetime Limits on Supersymmetric Particles from a Proton Beam-Dump Experiment

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Muonless events from the prompt-neutrino experiment at Fermilab have been analyzed to set limits on the masses and decays of supersymmetric particles by means of three measurements: (1) the ν_e/ν_μ ratio, (2) the rate of events consisting of electromagnetic showers only, and (3) the event rate at large transverse momentum. These limits are based upon the absence of events above our visible energy cutoff of 20 GeV which could be attributed to supersymmetry. Several hypotheses concerning supersymmetric particle decays are considered.

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In supersymmetric theories,[1,2] bosons and fermions are contained in the same multiplets. It is proposed that there are boson partners for all fermions and fermion partners for all bosons. The fermion partners for the gluon and photon are called the gluino ($\tilde{g}$) and the photino ($\tilde{\gamma}$), respectively. The breaking of global supersymmetry gives rise to a Goldstone fermion ($\tilde{G}$). In this paper we will be discussing gluinos, photinos, Goldstone fermions, and scalar quarks.

In some models[2] the gluino masses are estimated to be ~ 1–2 GeV and the lowest scalar-quark masses are less than $(0.5–1)m_Z$, where m_Z (about 93 GeV) is the mass of the neutral intermediate vector boson. Investigations of published data have set lower limits on the gluino mass in the 1–2-GeV range.[3] Similarly, the lowest scalar-quark mass must be $\geqslant 15$ GeV.[4]

Here we present results of an analysis of data obtained in the Fermilab prompt-neutrino experiment[5–7] and obtain more stringent limits on the masses and lifetimes of these supersymmetric particles. The experiment was designed to study the characteristics of the flux of penetrating neutral particles produced in the interactions of 400-GeV protons in a target-beam dump. The detector is a 48-metric-ton (fiducial volume) lead-scintillator calorimeter located 56 m from the target. A solid-iron–drift-chamber magnetic spectrometer following the calorimeter was used to identify muons produced in the detector.

Supersymmetric-particle events would appear in our muonless event sample as an excess above that expected from neutrino interactions. The muonless event sample, described more fully in Ref. 6, is that sample of events without a particle track passing through the spectrometer. The total experimental run amounted to 1.8×10^{17} protons on target (POT). Three experimental observations are used to set limits on the production of supersymmetric particles.

(1) The ratio of ν_e to ν_μ flux is $0.95 \pm 0.12 \pm 0.08$

above 20 GeV visible energy (see Ref. 6). The ν_e flux was obtained by subtracting from the muonless event sample the ν_μ-induced charged- and neutral-current events with the assumption that the neutral-current coupling to ν_e is the same as that to ν_μ. The subtraction was thus based on the observed ν_μ charged-current events. At the 90% confidence level (CL), calculated with use of the linear sum of the statistical and systematic errors, the upper limit for a possible signal for the decay of new particles is 0.21 of the prompt-ν_μ charged-current events, i.e., < 100 events per 10^{17} POT.

(2) Each of the thirty calorimeter modules in this experiment is 0.5 pion-interaction-lengths and 14 radiation-lengths long. As experimentally verified in a test beam of electrons, purely electromagnetic showers are contained in less than two or three modules (depending on the location of the vertex within a module). The muonless event sample was examined for events with showers less than four modules in length and without isolated tracks in the proportional wire planes which are interspersed between the modules. We observed 68.5 ± 12 such events per 10^{17} POT in the muonless event sample.

Events of this type are expected from quasielastic ν_e scattering and from deep-inelastic ν_e events in which the shower length is short as a result of a fluctuation in its development. The number of expected events should be equal to the number of charged-current interactions for which the hadronic shower is less than four modules in length (82 ± 15 events per 10^{17} POT), since replacement of the muon by the electron will not increase the shower length. This implies that the signal of purely electromagnetic decays of new particles is smaller than 11 events per 10^{17} POT at the 90% CL.

(3) The transverse momentum of the particles interacting in the calorimeter is determined by the visible energy of the event and the position of the vertex relative to the beam center line. For $1.5 < p_\perp < 2.2$ GeV/c we observe a total of 2.6 ± 6.4 events per 10^{17} POT. For the prompt muonless events due to neutrinos from charmed particles, we expect no events in our exposure for $p_\perp > 1.5$ GeV/c. At the 90% CL, therefore, the upper limit for a possible signal in this $p_\perp$ range is 11 muonless events per 10^{17} POT.

To compare with these data we require a model for the production and interaction cross sections of supersymmetric particles. The original attempt to calculate these cross sections and to search for supersymmetric particles in beam-dump experiments was due to Farrar and Fayet.[3] The photino and Goldstone-fermion interaction cross sections were first calculated by Fayet.[8] For this analysis the calculation by Kane and Leveille[9] for production of (colored) gluinos was used. In this model, the total cross section for gluino pair production by 400-GeV protons is 5.8×10^{-28}, 1.2×10^{-29}, 6.5×10^{-31}, 5.4×10^{-32}, 5.6×10^{-33}, and 6.4×10^{-34} cm^2 for gluino mass of $m_{\tilde g} = 1$, 2, 3, 4, 5, and 6 GeV, respectively. The invariant differential cross section is proportional[10] to $(1-|X_\mathrm{F}|)^5\exp(-2.2m_\perp)$, where X_F is the Feynman X of the gluino and $m_\perp = (m_{\tilde g}^2 + p_\perp^2)^{1/2}$. The dependence of the cross section on nuclear size is expected to be the same as for charm production. We present results here for both an $A^{0.72}$ and an A^1 dependence.

The gluino is assumed to decay before 10 cm (one interaction length in the tungsten target) and thus before further interaction in the target. For cases 1, 2, and 3 below it is assumed that the dominant decay mode of the gluino is

$$\tilde g \rightarrow \tilde\gamma q\bar q$$

and that the momentum distribution of the outgoing photino is given by[10]

$$E'\frac{d\Gamma}{d^3l'} = \frac{12\Gamma_0}{\pi m_{\tilde g}^6}\, l'\cdot q\,(m_{\tilde g}^2 - \tfrac{4}{3}l'\cdot q),$$

where the gluino has four-momentum q and the photino has four-momentum l'. Γ_0 is the gluino width, and the mass of the photino is assumed to be small.

For case 4 it is assumed that the dominant gluino decay is $\tilde g \rightarrow \tilde G g$, where $\tilde G$ is a Goldstone fermion.

We have examined four different possibilities, based on the gluino-decay mode and the photino lifetime:

Case 1.—The gluino decays into a photino; the photino is long lived and interacts in the calorimeter 56 m from the target. The cross section for the photino interaction is defined in terms of a parameter, $\tilde c$, as $\sigma = \tilde c E \times 10^{-38}$ cm^2. If the $\tilde\gamma$ interacts via a scalar quark[8,9,11] $\tilde q$, then $\tilde c = \tilde d(m_W/m_{\tilde q})^4$, where $\tilde d \cong 2.7$, 1.8, 1.1, 0.63, 0.34, and 0.16 for $m_{\tilde g} = 1$, 2, 3, 4, 5, 6 GeV. The limiting values derived from the transverse momentum distribution (experimental observation 3) and the overall limit on the ratio of anomalous events to ν_μ charged-current events (experimental observation 1) are used here and in cases 2 and 4 below. In Fig. 1 the 90% CL limits are plotted for $m_{\tilde g}$ as a function of $m_{\tilde q}/m_W$. As an example note that from Fig. 1 the 90% CL limit is $m_{\tilde g} > 4.1$ GeV for $m_{\tilde q} = 0.5M_W$ and σ proportional to $A^{0.72}$.

Case 2.—The gluino decays into a short-lived

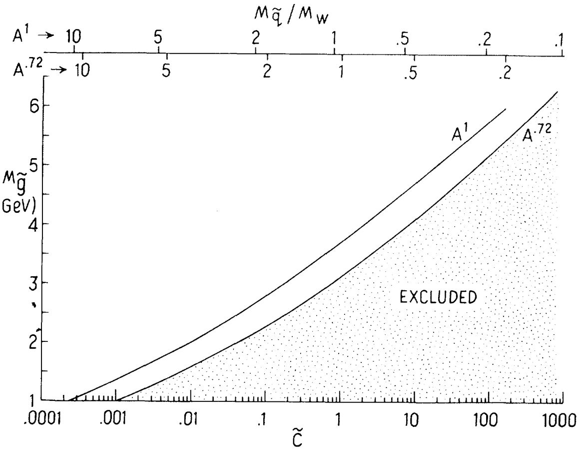

FIG. 1. $m_{\tilde{g}}$ vs $\tilde{c}$ for case 1 ($\tilde{g} \rightarrow \tilde{\gamma} q\bar{q}$; $\tilde{\gamma}$ long lived and interacts in calorimeter with $\sigma = \tilde{c}E \times 10^{-38}$ cm^2). 90% CL limits.

photino; the photino decays before reaching the detector into a Goldstone fermion and a photon.[12] We assume that the Goldstone fermion goes in the same direction as the photino. The Goldstone fermion interacts via a Goldstone-fermion–scalar quark–quark coupling[8] and a Goldstone fermion–gluino–gluon coupling.[9] In our experiment for gluino masses below (above) about 2 GeV the first (second) coupling would dominate. The cross section for Goldstone-fermion interaction by the first (second) coupling is $\sigma = (\alpha_s/0.15)(0.005/\Lambda_{ss}^4)E \times 10^{-38}$ cm^2 $[\sigma = 0.37(m_{\tilde{g}}^2/\Lambda_{ss}^4)(1-|X_F|)^5 \times 10^{-38}$ cm$^2]$. α_s, the strong interaction coupling constant, is taken here as 0.15. $m_{\tilde{g}}$ is in gigaelectronvolts. X_F is the Feynman X of the Goldstone fermion. Λ_{ss}, the supersymmetry-breaking parameter, is in teraelectronvolts. We have ignored any phase-space factor due to gluino mass. The resulting 90% CL lower limits for the value of Λ_{ss} are given in Table I. At each gluino mass we have used the coupling giving the higher limit.

Case 3.—The gluino decays into a photino with an intermediate lifetime; the decay of the photino is detected in the calorimeter. A region can be excluded for the ratio of photino lifetime to photino mass, $\tau_{\tilde{\gamma}}/m_{\tilde{\gamma}}$, since for long lifetimes very few photinos decay in the calorimeter and for short lifetimes very few get there at all. This region is derived from the limit on the rate of purely electromagnetic events in the calorimeter (experimental observation 2). The photino lifetime is taken[12] as $\tau_{\tilde{\gamma}} = 10^{-15}(\Lambda_{ss}/m_W)^4[(1\text{ GeV})/m_{\tilde{\gamma}}]^5$. As a result correlated values of $m_{\tilde{\gamma}}$ and Λ_{ss} can be excluded. This is shown in Table II and as an excluded region of the $m_{\tilde{\gamma}}$ and Λ_{ss} plane (Fig. 2). Note that on the left-hand side of the excluded region in Fig. 2 the limits of case 2 apply and on the right-hand side the limits of case 1 apply.

TABLE I. Lower limits for Λ_{ss} (TeV) for case 2 ($\tilde{g} \rightarrow \tilde{\gamma} q\bar{q}$ and $\tilde{\gamma} \rightarrow \tilde{G}\gamma$ before the detector) and case 4 ($\tilde{g} \rightarrow \tilde{G}g$) assuming $\sigma \propto A^{0.72}$. The limits for $\sigma \propto A^1$ are 1.44 times larger.

$m_{\tilde{g}}$ (GeV)	Λ_{ss} (TeV) (90% CL limit) Case 2	Case 4
1	1.18	2.25
2	0.48	0.87
3	0.29	0.45
4	0.18	0.26
5	0.12	0.15
6	0.08	0.091

Two photinos couple through scalar-electron exchange to e^+e^-. The present experiment, together with results from PETRA[13,14] and PEP,[15,16] excludes combinations of gaugino and scalar "fermion" masses and the supersymmetry-breaking parameters, the present experiment covering the cases in which $m_{\tilde{\gamma}} < m_{\tilde{g}} < \sim 5$ GeV. The PETRA and PEP limits fill in the triangular region at the top of Fig. 2.[12]

Case 4.—The gluino decays into a Goldstone fermion and a gluon; the Goldstone fermion interacts in the calorimeter. Within the model considered here the Goldstone-fermion is stable and light. The cross section for a Goldstone fermion to interact is the same as in case 2. The results are shown in Table I.

The validity of the calculations used here is strongly supported by the fact that within supersym-

TABLE II. Excluded regions of photino lifetime for case 3 ($\tilde{g} \rightarrow \tilde{\gamma} q\bar{q}$; $\tilde{\gamma} \rightarrow \tilde{G}\gamma$; $\tilde{\gamma}$ decay seen in calorimeter).

$m_{\tilde{g}}$ (GeV)	$\tau_{\tilde{\gamma}}/m_{\tilde{\gamma}}$ (s/GeV) (excluded at the 90% CL limit) $\sigma \propto A^{0.72}$	$\sigma \propto A^1$
1	3.1×10^{-11}–1.04×10^4	2.9×10^{-11}–4.5×10^4
2	4.7×10^{-11}–206	4.4×10^{-11}–883
3	5.8×10^{-11}–11.0	5.4×10^{-11}–48
4	6.3×10^{-11}–0.76	5.8×10^{-11}–3.3
5	7.2×10^{-11}–0.075	6.5×10^{-11}–0.32
6	7.9×10^{-11}–7.4×10^{-3}	7.0×10^{-11}–0.032

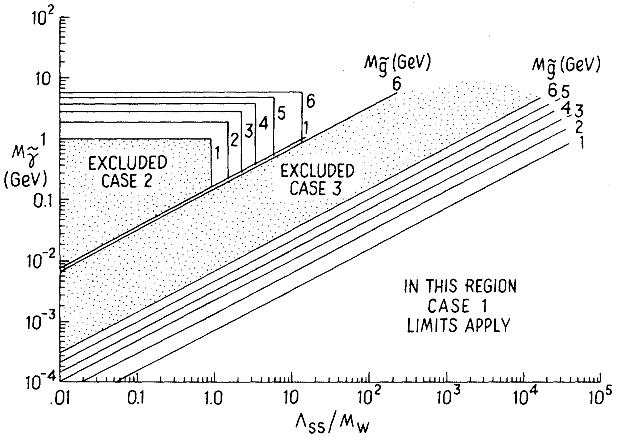

FIG. 2. $m_{\tilde{\gamma}}$ vs Λ_{ss} for case 2 ($\tilde{g} \rightarrow \tilde{\gamma} q\bar{q}$; $\tilde{\gamma} \rightarrow \tilde{G}\gamma$ and $\tilde{G}$ interacts) and case 3 ($\tilde{g} \rightarrow \tilde{\gamma} q\bar{q}$; $\tilde{\gamma}$ decays in calorimeter and photon interacts). The shaded region of gluino mass and Λ_{ss}/m_W is excluded. The limits were drawn under assumption of $A^{0.72}$ production cross section. The lower limits for case 3 would be a factor 1.27 lower for A^1. The vertical-line limits for case 2 would be a factor 1.44 higher for A^1. The other limits are essentially the same for $A^{0.72}$ or A^1 production cross section.

metry the interactions of a supersymmetric particle are completely determined by the known interactions of its conventional partner. Because the limits relate to the fourth root of the number of observed events, they are not very sensitive to details of the model and thus provide sharp constraints for supersymmetric theories.

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