Search for Squarks and Gluinos in Single-Photon Events with Jets and Large Missing Transverse Energy in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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(August 13, 1998)

We search for physics beyond the standard model using events with a photon, two or more hadronic jets, and an apparent imbalance in transverse energy, in $p\bar{p}$ collisions at the Fermilab Tevatron at $\sqrt{s} = 1.8$ TeV. Such events are predicted for production of supersymmetric particles. No excess is observed beyond expected background. For the parameter space of the minimal supersymmetric standard model with branching fraction $\mathrm{B}(\tilde{\chi}_2^0 \rightarrow \gamma\tilde{\chi}_1^0) = 1$ and $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} > 20$ GeV, we obtain a 95% confidence level lower limit of 310 GeV for the masses of squarks and gluinos, where their masses are assumed equal.

We search for physics beyond the standard model (SM) using events with one high transverse energy (E_T) photon, two or more jets, and large imbalance in transverse energy ($\not{E}_T$). We call these $\gamma\not{E}_T + \geq 2$ jets events. This search is motivated by recent suggestions [1,2] that supersymmetry may result in signatures involving one or more photons together with multiple jets and large $\not{E}_T$.

Supersymmetry is a generalization of space-time symmetry. It introduces for every particle in the standard model a supersymmetric partner differing in spin by one half. R-parity [3], defined as $+1$ for SM particles and -1 for their super-partners, is assumed to be conserved in this analysis, such that supersymmetric particles are produced in pairs and the lightest supersymmetric particle (LSP) is stable. In the minimal supersymmetric standard model (MSSM), 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. Gaugino-Higgsino mixing gives four neutral mass eigenstates (neutralinos $\tilde{\chi}_i^0,\ i = 1, ..., 4$) and two charged mass eigenstates (charginos $\tilde{\chi}_i^{\pm},\ i = 1, 2$). Within the MSSM, the radiative decay of $\tilde{\chi}_2^0 \to \gamma\tilde{\chi}_1^0$ dominates in the region $50 \lesssim M_1 \sim M_2 \lesssim 100$ GeV, $1 \lesssim \tan\beta \lesssim 3$ and $-65 \lesssim \mu \lesssim -35$ GeV of parameter space [4], and has been proposed as an explanation [2] of a candidate event reported by the CDF Collaboration [5]. Assuming that $\tilde{\chi}_1^0$ is the LSP, then the production of $\tilde{\chi}_2^0$, either directly or from decays of other supersymmetric particles, will yield $\gamma\not{E}_T + X$ events.

In this Letter, we present a search for physics beyond the SM in the channel $p\bar{p} \to \gamma\not{E}_T + \geq 2$ jets at the Fermilab Tevatron collider. Because of large backgrounds from QCD processes, we do not consider events with less than two jets. We interpret our results in terms of squark ($\tilde{q}$) and gluino ($\tilde{g}$) production in the context of supersymmetric models with a dominant $\tilde{\chi}_2^0 \to \gamma\tilde{\chi}_1^0$ decay.

The data used in this analysis were collected with the DØ detector during the 1992–1996 Tevatron run at a center of mass energy of $\sqrt{s} = 1.8$ TeV, and represent an integrated luminosity of 99.4 ± 5.4 pb^{-1}. A detailed description of the DØ detector can be found in Ref. [6]. The trigger requires one electromagnetic (EM) cluster with $E_T > 15$ 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). Photons are identified via a two-step process: the selection of isolated EM energy clusters, and the rejection of such clusters with any associated charged tracks. 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 with radius ($\mathcal{R} \equiv \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$) 0.2 to 0.4 around the cluster in $\eta - \phi$ space to be less than 10% of the EM energy in an $\mathcal{R} = 0.2$ cone, where η and ϕ are the pseudorapidity and azimuth, respectively. The EM clusters that have either a reconstructed track or a large number of hits in the tracking chamber along a road joining the cluster and the interaction vertex are vetoed. $\not{E}_T$ is determined from the energy deposition in the calorimeter within $|\eta| < 4.5$.

To be selected as $\gamma\not{E}_T + \geq 2$ jets candidates, events are first required to have at least one identified photon with $E_T^{\gamma} > 20$ GeV and pseudorapidity $|\eta^{\gamma}| < 1.1$ or $1.5 < |\eta^{\gamma}| < 2.0$, and two or more jets reconstructed with cones of radius $\mathcal{R} = 0.5$, having $E_T^j > 20$ GeV and $|\eta^j| < 2.0$. We refer to the events passing these requirements as the $\gamma + \geq 2$ jets sample. The $\not{E}_T$ distribution of these events is shown in Fig. 1. We then require $\not{E}_T > 25$ GeV. A total of 318 events satisfy all requirements.

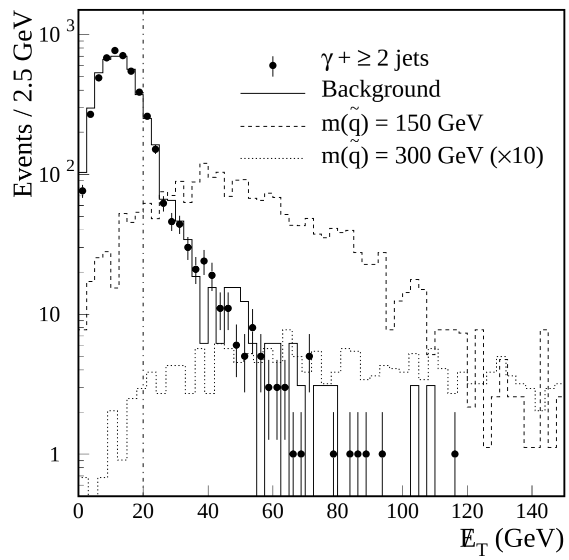

FIG. 1. The $\not{E}_T$ distributions of the $\gamma + \geq 2$ jets (solid circles) and background (solid histogram) events. The number of events in the background is normalized to the $\gamma + \geq 2$ jets sample for $\not{E}_T < 20$ GeV, the region left of the dot-dashed line. Also shown (dashed and dotted histograms) are the distributions expected from supersymmetry for $m_{\tilde{q}} = m_{\tilde{g}} = 150$ GeV and 300 GeV.

The principal backgrounds to the signal are: events from sources such as QCD direct photon and multijet events, where there is mismeasured $\not{E}_T$ and a real or fake photon; $W(\to e\nu)$ + jets events, where the electron is misidentified as a photon; and $W(\to \ell\nu)$ + jets events (where $\ell = e, \mu, \tau$), in which one of the jets is misidentified as a photon. These backgrounds are estimated from the data sample with the same trigger as the candidate events. The background from mismeasurement of $\not{E}_T$ is estimated using events with one EM-like cluster that satisfies all photon criteria, except requirement (ii) on the shower profile. These events must also have two or more jets with $E_T^j > 20$ GeV and $|\eta^j| < 2.0$, making them similar to those of the $\gamma + \geq 2$ jets sample, and therefore of similar resolution in $\not\!\!E_T$. The events in this background sample are normalized to the $\gamma + \geq 2$ jets sample for $\not\!\!E_T < 20$ GeV, which provides an estimated background from $\not\!\!E_T$ mismeasurement of 315 ± 30 events beyond $\not\!\!E_T = 25$ GeV.

$W + \geq 2$ jets events with $W \to e\nu$ can mimic $\gamma\not\!\!E_T + \geq 2$ jets events if the electron is misidentified as a photon. This contribution is estimated using a sample of $e\not\!\!E_T + \geq 2$ jets events that passes all our kinematic requirements, with the electron satisfying those defined for the photon. Electrons are selected from identified EM clusters that have matched tracks. The probability that an electron is misidentified as a photon is determined from $Z \to ee$ events as 0.0045 ± 0.0008. Multiplying this probability by the number of $e\not\!\!E_T + \geq 2$ jets events yields a background of 4 ± 1 events.

The $W(\to \ell\nu) +$ jets background is estimated using a data sample of $W(\to e\nu) + \geq 3$ jets events passing all kinematic requirements, with at least one of the jets satisfying those imposed on photons. The probability that a jet is misidentified as a photon is determined by counting the number of photons observed in multijet events. We find this to be 0.0007 ± 0.0002. Using this probability and the scale factor $N_{W(\to\ell\nu)+\geq 3 \text{ jets}}/N_{W(\to e\nu)+\geq 3 \text{ jets}}$ (determined from Monte Carlo), we estimate a background of 1.0 ± 0.3 events. The background from $Z(\to \nu\nu) + \geq 3$ jets is found to be negligible.

Number of jets	$\not\!\!E_T > 25$ GeV No H_T cut		$\not\!\!E_T > 25$ GeV $H_T > 200$ GeV		$\not\!\!E_T > 50$ GeV No H_T cut	
	N_S	N_B	N_S	N_B	N_S	N_B
$n \geq 2$	318	320±30	30	20±10	43	65±15
$n \geq 3$	70	70±15	17	8±5	11	10±5
$n \geq 4$	8	10±5	6	4±3	1	3±3

TABLE I. Number of observed $\gamma\not\!\!E_T + n$ jets events (N_S) together with the corresponding number of background events (N_B) for $n \geq 2, 3, 4$, for three sets of cutoffs.

The number of observed events and the expected backgrounds are summarized in Table I, together with breakdowns into events with three or more and four or more jets. The H_T distribution (defined as the scalar sum of the E_T of all jets with $E_T^j > 20$ GeV and $|\eta^j| < 2.0$) is shown in Fig. 2, for both $\gamma\not\!\!E_T + \geq 2$ jets and background samples. The background distribution is consistent with that observed for $\gamma\not\!\!E_T + \geq 2$ jets. Also given in Table I is the number of observed events and the expected background if the cutoff $H_T > 200$ GeV is applied or if the $\not\!\!E_T$ cutoff is raised to 50 GeV. In all three comparisons, the estimated number of background events agrees with the number of events observed in the data.

To optimize selection criteria for a supersymmetric signal, we simulate squark and gluino pair production, and also production in association with charginos or neutralinos using the SPYTHIA program [7]. The MSSM parameters are set to $M_1 = M_2 = 60$ GeV, $\tan\beta = 2$, and $\mu = -40$ GeV. This set gives $m_{\tilde{\chi}_1^0} = 34$ GeV, $m_{\tilde{\chi}_2^0} = 60$ GeV, and $\mathrm{B}(\tilde{\chi}_2^0 \to \gamma\tilde{\chi}_1^0) = 1$. Sleptons ($\tilde{\ell}$) and stop ($\tilde{t}_1$) are assumed to be heavy. Events with $\tilde{\chi}_2^0$ in the final state are selected and processed through the DØ detector-simulation program [8], and the trigger simulator. The same trigger requirements, reconstruction, and selection criteria are then applied as were used with the data. Monte Carlo (MC) events are generated for three squark or gluino mass possibilities: (i) equal mass squark and gluino ($m_{\tilde{q}} = m_{\tilde{g}}$); (ii) heavy squark and light gluino ($m_{\tilde{q}} \gg m_{\tilde{g}}$); and (iii) light squark and heavy gluino ($m_{\tilde{q}} \ll m_{\tilde{g}}$). The $\not\!\!E_T$ and H_T distributions for $m_{\tilde{q}} = m_{\tilde{g}} = 150, 300$ GeV events are shown, respectively, in Figs. 1 and 2, where the MC distributions are scaled by the factors shown in parentheses. The distributions expected from supersymmetry differ considerably from those of the background. To increase the sensitivity to supersymmetry, we introduce an H_T cutoff, and maximize the $\epsilon_S/\delta N_B$ ratio by varying the $\not\!\!E_T$ and H_T cutoffs. Here ϵ_S is the efficiency for signal, and δN_B is the uncertainty on the estimated number of background events. To ensure high efficiencies for both low and high squark and gluino masses, the optimization is done for two MC points $m_{\tilde{q}} = m_{\tilde{g}} = 150$ and 300 GeV. The optimum values are $\not\!\!E_T > 35$ GeV and $H_T > 100$ GeV for 150 GeV, and $\not\!\!E_T > 45$ GeV and $H_T > 220$ GeV for 300 GeV. The $\epsilon_S/\delta N_B$ results (a function of squark/gluino mass) for the two sets of optimized cutoffs are equal near 200 GeV. Therefore we apply the cutoffs optimized for the 150 GeV mass point to MC events with squark and

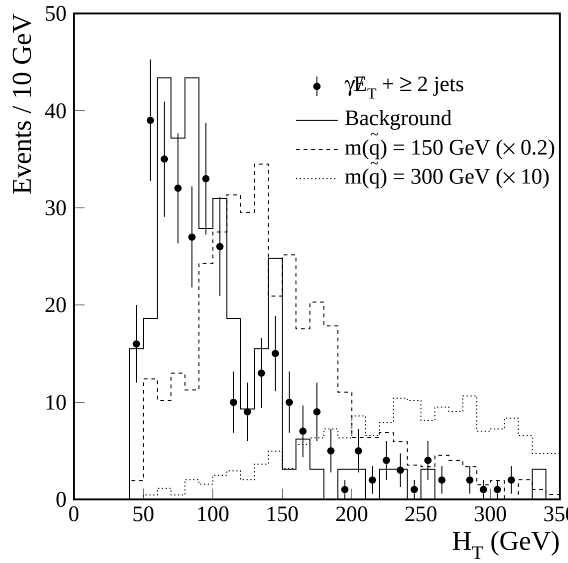

FIG. 2. The H_T (defined as $\sum_j E_T^j$) distributions of the $\gamma\not\!\!E_T + \geq 2$ jets and background events. The expected distributions from supersymmetry are also shown for comparison.

gluino masses below 200 GeV, and apply those optimized for the 300 GeV mass point to masses of 200 GeV or above. The number of events observed for these two sets of cutoffs are 60 and 5, with 75 ± 17 and 8 ± 6 events expected from background processes. We consequently observe no excess beyond the standard model.

$m_{\tilde{q}/\tilde{g}}$	$m_{\tilde{q}}(= m_{\tilde{g}})$		$m_{\tilde{g}}(\ll m_{\tilde{q}})$		$m_{\tilde{q}}(\ll m_{\tilde{g}})$	
GeV	ϵ_0 (%)	ϵ_S (%)	ϵ_0 (%)	ϵ_S (%)	ϵ_0 (%)	ϵ_S (%)
150	66.2	15.1±0.8	69.1	11.6±0.9	60.0	16.8±1.1
200	62.3	7.9±0.6	59.6	5.3±0.6	53.8	9.5±0.9
250	59.6	14.8±0.8	49.7	13.6±1.1	55.4	14.8±1.1
300	56.1	21.5±1.0	43.1	19.0±1.3	55.4	22.1±1.2
350	51.8	22.8±1.1	39.3	23.5±1.5	52.7	26.6±1.4
400	46.7	23.5±1.1	33.3	22.7±1.6	54.3	25.8±1.3

TABLE II. The percentages of events (ϵ_0) generated containing $\tilde{\chi}_2^0$ in the final state, and the efficiencies (ϵ_S) for their detection using the two sets of optimized cutoffs as discussed in the text, for different values of squark/gluino mass. The uncertainties are purely statistical.

The detection efficiencies (ϵ_S) for predictions from the supersymmetric models are given in Table II, along with the percentages (ϵ_0) of generated events having $\tilde{\chi}_2^0$ in the final state. MC studies show that the overall efficiency varies by 4% for different choices of M_1, M_2, $\tan\beta$, and μ that are consistent with $\mathrm{B}(\tilde{\chi}_2^0 \to \gamma\tilde{\chi}_1^0) = 1$ and $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} > 20$ GeV, the suggestions offered in Ref. [2]. Experimentally, the mass requirement is needed to ensure that photons from $\tilde{\chi}_2^0$ decays are reasonably energetic and can be detected with good efficiency. The total systematic error on the efficiency is 9%, including uncertainties in photon identification efficiency (7%), the choice of values of the supersymmetry parameters (4%), and the jet energy scale (3%).

We set a 95% confidence level (C.L.) upper limit on $\sigma \times \mathrm{B} \equiv \sigma(p\bar{p} \to \tilde{q}/\tilde{g} \to \tilde{\chi}_2^0 + X) \times \mathrm{B}(\tilde{\chi}_2^0 \to \gamma\tilde{\chi}_1^0)$ using a Bayesian approach with a flat prior distribution for the signal cross section. The statistical and systematic uncertainties on the efficiency, the integrated luminosity, and the background estimate are included in the calculation of the limit, assuming Gaussian prior distributions. The resulting upper limit as a function of squark/gluino mass is tabulated in Table III.

$m_{\tilde{q}/\tilde{g}}$	$\sigma \times$ B (pb)					
	$m_{\tilde{q}}(= m_{\tilde{g}})$		$m_{\tilde{g}}(\ll m_{\tilde{q}})$		$m_{\tilde{q}}(\ll m_{\tilde{g}})$	
GeV	Theory	Limit	Theory	Limit	Theory	Limit
150	83.4	2.0	24.1	2.6	8.51	1.8
200	12.1	1.1	3.48	1.6	1.59	0.9
250	2.37	0.57	0.51	0.63	0.43	0.58
300	0.53	0.39	0.12	0.44	0.12	0.38
350	0.13	0.37	0.02	0.37	0.03	0.32
400	0.04	0.36	0.01	0.37	0.01	0.32

TABLE III. The theoretical cross section $\sigma \times$ B and our measured 95% confidence level upper limit on $\sigma \times$ B for different values of squark/gluino mass. The predictions are calculated for $M_1 = M_2 = 60$ GeV, $\tan\beta = 2$, and $\mu = -40$ GeV.

Figure 3 shows the limit for the case where $m_{\tilde{q}} = m_{\tilde{g}}$, together with the leading-order theoretical cross section, calculated using the SPYTHIA program with the CTEQ3L parton distribution functions [9]. The renormalization scale (μ_{RS}) is set to the average transverse energy ($\langle E_T \rangle$) of the outgoing partons in the calculation. The cross section varies by about ±30% if $\mu_{RS} = 2\langle E_T \rangle$ or $\mu_{RS} = \langle E_T \rangle/2$ is used. The hatched band represents the range of predictions obtained by varying the supersymmetry parameters with the constraints that $\mathrm{B}(\tilde{\chi}_2^0 \to \gamma\tilde{\chi}_1^0) = 1$ and $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} > 20$ GeV, assuming $\mu_{RS} = \langle E_T \rangle$. The intersection of the limit with the lower edge of the band is at $\sigma \times \mathrm{B} = 0.38$ pb, leading to a lower limit for equal mass squarks and gluinos of 310 GeV at the 95% C.L.

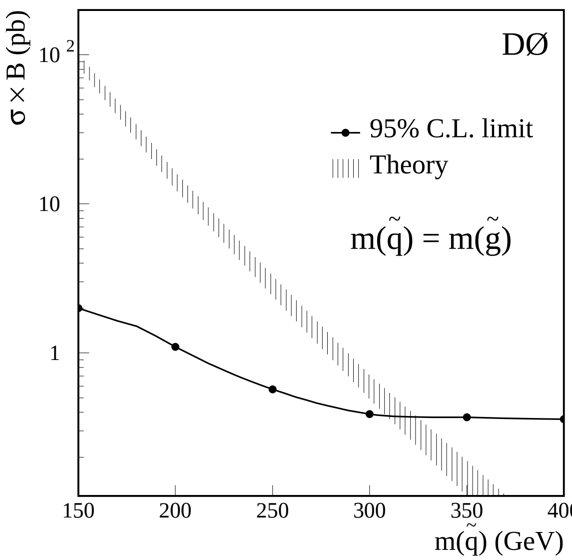

FIG. 3. The 95% C.L. upper limit on $\sigma \times$ B as a function of $m_{\tilde{q}/\tilde{g}}$, assuming equal squark and gluino masses. The hatched band represents the range of expected cross sections for different sets of MSSM parameters, consistent with the constraints $\mathrm{B}(\tilde{\chi}_2^0 \to \gamma\tilde{\chi}_1^0) = 1$ and $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} > 20$ GeV. The inflection below 200 GeV in the limit curve is the intersection of the two curves using the two sets of optimized cutoffs discussed in the text.

The effect of light sleptons on squark and gluino decays is studied by varying the slepton mass ($m_{\tilde{\ell}} = m_{\tilde{e}} = m_{\tilde{\mu}} = m_{\tilde{\tau}}$) from 500 GeV to 80 GeV in the MC. For $m_{\tilde{q}} = m_{\tilde{g}} = 300$ GeV MC events, the percentage ϵ_0 increases by an additional 25%. Sleptons with mass below 80 GeV have already been excluded [10]. The increase in $\tilde{\chi}_2^0$ production increases the mass limit by approximately 10 GeV.

A light stop $\tilde{t}_1$ would also modify squark and gluino decays and would therefore affect $\tilde{\chi}_2^0$ production. If $m_{\tilde{t}_1}$ is lowered from 500 GeV to the lower experimental limit of 80 GeV [10,11], a 15% reduction in $\tilde{\chi}_2^0$ production is predicted. This reduction lowers the limit for equal mass squarks and gluinos by about 6 GeV.

Following the above procedure, we obtain a lower limit for gluino (squark) mass of 240 GeV when squarks (gluinos) are heavy. Again, these limits vary by approximately 10 GeV if $\tilde{t}_1$ and/or sleptons are light.

In summary, we have searched for an excess of $\gamma \not\!\!E_T$ events with two or more jets in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. Such events are predicted in the minimal supersymmetric standard model. We find that the number of observed $\gamma \not\!\!E_T + \geq 2$ jets events agrees well with that expected from background processes. Within the framework of the MSSM, with choices of parameters consistent with $\mathrm{B}(\tilde{\chi}_2^0 \to \gamma\tilde{\chi}_1^0) = 1$ and $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} > 20$ GeV, we obtain a 95% C.L. lower mass limit of 310 GeV for equal mass squarks and gluinos and of 240 GeV for squarks (gluinos) when gluinos (squarks) are heavy. These limits constrain the models discussed in Ref. [2], but do not exclude all of them.

We thank the staffs at Fermilab and collaborating institutions for their contributions to this work, and acknowledge support from the Department of Energy and National Science Foundation (U.S.A.), Commissariat à L'Energie Atomique (France), Ministry for Science and Technology and Ministry for Atomic Energy (Russia), CAPES and CNPq (Brazil), Departments of Atomic Energy and Science and Education (India), Colciencias (Colombia), CONACyT (Mexico), Ministry of Education and KOSEF (Korea), and CONICET and UBACyT (Argentina).

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[1] 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).

[2] S. Ambrosanio *et al.*, Phys. Rev. Lett. **76**, 3498 (1996) and Phys. Rev. D **55**, 1372 (1997).

[3] G.R. Farrar and P. Fayet, Phys. Lett. B **76**, 575 (1978).

[4] 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), Erratum-ibid. **56**, 3157 (1997).

[5] CDF Collaboration, F. Abe *et al.*, `hep-ex/9801019`, submitted to Phys. Rev. Lett; `hep-ex/9806034`, submitted to Phys. Rev. D.

[6] DØ Collaboration, S. Abachi *et al.*, Nucl. Instrum. Methods A **338**, 185 (1994).

[7] T. Sjöstrand, Comp. Phys. Commun. **82**, 74 (1994); S. Mrenna, Comp. Phys. Commun. **101**, 232 (1997). We used SPYTHIA version 5.7.

[8] R. Brun and F. Carminati, CERN Program Library Long Writeup W5013, 1993 (unpublished).

[9] H.L. Lai *et al.*, Phys. Rev. D **51**, 4763 (1995).

[10] ALEPH Collaboration, R. Barate *et al.*, CERN-EP/98-077, submitted to Phys. Lett. B; CERN-EP/98-076, submitted to Phys. Lett. B; L3 Collaboration, M. Acciarri *et al.*, CERN-PPE/97-130, to be published in Euro. Phys. Journal C.

[11] DØ Collaboration, S. Abachi *et al.*, Phys. Rev. Lett. **76**, 2222 (1996).