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CDF

**Search for New Physics in Diphoton Events in
 $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV**

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Searches for New Physics in Diphoton Events in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV

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Abstract

We have searched for anomalous production of missing E_T (\cancel{E}_T), jets, leptons (e, μ, τ), b -quarks, or additional photons in events containing two isolated, central ($|\eta| < 1.0$) photons with $E_T > 12$ GeV. The results are consistent with standard model expectations, with the possible exception of one event that has in addition to the two photons a central electron, a high- E_T electromagnetic cluster, and large \cancel{E}_T . We set limits using two specific SUSY scenarios for production of diphoton events with \cancel{E}_T .

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In many models involving physics beyond the standard model (SM), cascade decays of heavy new particles generate $\gamma\gamma$ signatures involving missing transverse energy (\cancel{E}_T), jets, leptons, gauge bosons (W, Z^0, γ), and possibly b -quarks [1]. For example, in supersymmetric models with a light gravitino, pair-production of selectrons which decay via $\tilde{e} \rightarrow eN_1 \rightarrow e\gamma\tilde{G}$ produces the $\gamma\gamma$ final state along with \cancel{E}_T and electrons. In the data taken during 1993-1995, an ‘ $ee\gamma\gamma\cancel{E}_T$ ’ candidate event [2] was recorded with the CDF Detector [3]. We have performed a systematic search for other anomalous $\gamma\gamma$ events by examining events with two isolated, central ($|\eta| < 1.0$) photons with $E_T > 12$ GeV which contain \cancel{E}_T , jets, leptons (e, μ, τ), b -quarks, or additional photons [4]. This search is based on 85 ± 7 pb $^{-1}$ of data from $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV collected with the CDF detector. In this Letter we describe the results of the search, including the $ee\gamma\gamma\cancel{E}_T$ candidate event, and set limits on two SUSY models that have arisen to explain it.

We briefly describe here the relevant aspects of the CDF detector. The magnetic spectrometer consists of tracking devices inside a 3-m diameter, 5-m long superconducting solenoidal magnet which operates at 1.4 T. A four-layer silicon microstrip vertex detector (SVX) [5] is used to identify b hadron decays. A set of vertex time projection chambers (VTX) surrounding the SVX is used to find the z position of the $\bar{p}p$ interaction (z_{vertex}). The 3.5-m long central tracking chamber (CTC) is used to measure the momenta of charged particles. The calorimeter, constructed of projective electromagnetic and hadronic towers, is divided into a central barrel which surrounds the solenoid coil ($|\eta| < 1.1$), ‘end-plugs’ ($1.1 < |\eta| < 2.4$), and forward/backward modules ($2.4 < |\eta| < 4.2$). Wire chambers with cathode strip readout give 2-dimensional profiles of electromagnetic showers in the central and plug regions (CES and PES systems, respectively). A system of proportional wire chambers (CPR) in front of the central electromagnetic calorimeters uses the 1-radiation-length-thick magnet coil as a ‘preradiator’, allowing photon/ π^0 discrimination on a statistical basis by measuring the conversion probability [6]. Muons are identified with the central muon chambers, situated outside the calorimeters in the region $|\eta| < 1.1$.

The data sample selection starts with events with two photon candidates identified by the

three-level trigger [7]. At Level 1, events are required to have two electromagnetic calorimeter trigger-towers [8] with measured E_T of more than 4 GeV. At Level 2, we require the logical ‘OR’ of two triggers, one optimized for good background rejection at low E_T and the other for high efficiency at high E_T . The low-threshold diphoton trigger requires two electromagnetic clusters [9] with $E_T > 10$ GeV and an isolation requirement of less than 4 GeV in a 3-by-3 array of trigger-towers around the cluster; the high-threshold (16 GeV) trigger has no isolation requirement. Corresponding Level 3 triggers require cluster energies calculated with the offline photon algorithm [6] to be above the 10 GeV and 16 GeV thresholds. The low-threshold trigger also requires the clusters be in a restricted fiducial region of the calorimeter [10].

We use the following selection criteria offline: a) two isolated [11] central electromagnetic clusters with $E_T > 12$ GeV (where the 10 GeV trigger becomes $> 98\%$ efficient); b) no tracks, or only one track with $P_T < 1$ GeV, pointing at either cluster (to remove electrons or jets); c) pulse height and shape in the CES consistent with a shower due to a photon (to remove π^0 backgrounds); d) no other photon candidate within the same 15° segment of the CES (to remove π^0 backgrounds) [12]; e) $|z_{\text{vertex}}| < 60$ cm (to maintain the projective geometry of the calorimeter); and f) no energy out-of-time with the collision (to suppress cosmic rays) [13]. For events in which both photon candidates have $E_T > 22$ GeV (where the 16 GeV trigger becomes $> 98\%$ efficient) the fiducial and isolation requirements are relaxed [10,11]. The final data set consists of 2239 events.

The efficiency for identifying an isolated photon is measured using electrons in a control sample of 2663 $Z^0 \rightarrow e^+e^-$ decays to be $68 \pm 3\%$ for the 12 GeV selection criteria, and $84 \pm 4\%$ for the 22 GeV selection criteria, in each case approximately flat in E_T . Photon backgrounds are measured using the shower shape in the CES system for $E_T < 35$ GeV, where the difference between a single γ or $\pi^0 \rightarrow \gamma\gamma$ can be resolved, and the conversion probability in the CPR for $E_T > 35$ GeV [6]. Since the purity of the $\gamma\gamma$ sample is of less importance to searches for rare signatures than the efficiency, we have chosen selection criteria to keep the efficiency high; however these admit a substantial number of background

events. The fraction of events in the sample which contain two prompt photons is measured to be $15 \pm 4\%$.

We search the diphoton events for the presence of \cancel{E}_T , jets, electrons, muons, taus, b -quarks, and additional photons. To minimize the effect of fluctuations due to mismeasurement of jet energies, we recalculate the \cancel{E}_T by making jet energy corrections which take into account cracks between detector components and nonlinear calorimeter response [14,15]. In the $\gamma\gamma + \cancel{E}_T$ search we remove events which have a jet with uncorrected $E_T > 10$ GeV pointing within 10 degrees in azimuth of the \cancel{E}_T . The resulting resolution on either the x or y component of \cancel{E}_T , determined from a study of Z^0 bosons, is well-parameterized by $\sigma(\cancel{E}_T^x) = (2.66 \pm 0.34 \text{ GeV}) + (0.043 \pm 0.007) \times \Sigma E_T$, where ΣE_T does not include the E_T of either electron. The criteria for identifying jets (uncorrected $E_T > 10$ GeV and $|\eta| < 2.0$), electrons, muons and b -jets are identical to those used in the top-quark discovery [15]. The tau selection is the same as used in the study of $t\bar{t}$ decays into $e\tau$ and $\mu\tau$ final states [16]. Any third photon is required to have $E_T > 25$ GeV and to pass the high-threshold selection criteria.

Table I summarizes the observed and expected numbers of events. The distributions in \cancel{E}_T and the number of jets, N_{jet} , are shown in Figure 1. The shapes of the \cancel{E}_T distributions are in good agreement with the resolution derived from the Z^0 control sample, shown as the hatched region in Figures 1a and 1c. The distributions in N_{jet} are well-modeled by an exponential extrapolation, shown in Figures 1b and 1d. For a photon threshold of 12 GeV we observe 1 event with $\cancel{E}_T > 35$ GeV, with a SM expectation of 0.5 ± 0.1 , and 2 events with 4 or more jets, versus an expectation of 1.6 ± 0.4 . For a photon threshold of 25 GeV, we observe 2 events with $\cancel{E}_T > 25$ GeV, with 0.5 ± 0.1 expected, and 0 events with 3 or more jets, with 1.7 ± 1.5 expected.

We find 2 events with b -tags, consistent with background expectations, and no events with a third photon. There are 4 events with a central lepton: one event is consistent with a double-radiative Z^0 decay ($m_{\mu\mu\gamma\gamma} = 92 \pm 1 \text{ GeV}/c^2$), one is consistent with a radiative Z^0 decay with a lost track ($m_{ee\gamma} = 91 \pm 2 \text{ GeV}/c^2$), and one has a τ candidate, for which we

expect a fake background of 0.2 ± 0.1 events. From Table I and Figure 1, we find agreement between our observations and SM model predictions with one possible exception.

The event that has the largest \cancel{E}_T ($\cancel{E}_T = 55 \pm 7$ GeV) among all diphoton candidates, has in addition to the two high- E_T photons a central electron and an electromagnetic cluster in the plug calorimeter which passes the electron selection criteria used for Z^0 identification [17]. The 4-vectors are presented in Table II. Because the momenta of the four clusters are measured by the electromagnetic calorimeters, the resolution on each is a few per cent (see Table II). The total P_T of the 4-cluster system is 48 ± 2 GeV/c, opposite to the \cancel{E}_T and in good agreement with the measured magnitude, implying the imbalance is intrinsic to the 4-cluster system. The invariant mass of the electron and the electromagnetic cluster in the plug calorimeter is 163 ± 3 GeV/c², far from the Z^0 mass. The invariant mass of the 4-body system is 232 ± 4 GeV/c²; a lower limit on the invariant mass of the total system is found by including the \cancel{E}_T (taking $p_z = 0$), to be 307 ± 9 GeV/c².

Although the electromagnetic cluster in the plug calorimeter passes all of the standard electron selection criteria [17], there is no track in the SVX pointing directly at the cluster, as would be expected if the cluster were due to an electron [4,18]. There is, however, a track 26 mrad away in ϕ . Using a sample of 1009 electrons in the end-plug calorimeter from $Z^0 \rightarrow e^+e^-$ events, we estimate the resolution on ϕ to be 1.5 mrad; no events have a mismatch of greater than 20 mrad. The probability of an electron to have a ϕ mismatch this large is thus less than 0.3% at 95% C.L. The interpretation of the cluster as coming from an isolated photon, the 1-prong hadronic decay of a τ , or a jet, while possible, are also all unlikely in that this would be an unusual example of any of them [4]. We simply do not have enough information to establish the origin of the cluster.

We have estimated the SM rates for producing a signature of two photons, two electromagnetic clusters (one central) passing the electron requirements and \cancel{E}_T , all with $E_T > 25$ GeV, and $m_{ee} > 110$ GeV/c² (above the Z^0 boson) [4]. Using both data and Monte Carlo methods, we have considered production of SM $WW\gamma\gamma$ and $t\bar{t}$, as well as sources which include additional cosmic ray interactions, jets which fake electrons and/or photons,

and overlapping events. The total rate is 1×10^{-6} events, with the dominant sources being $WW\gamma\gamma$ (8×10^{-7} events) and $WW\gamma j$ (8×10^{-8} events). Removing sources where the plug cluster is due to a real electron, the rate is reduced to 6×10^{-8} events, with the dominant source being $W\gamma\gamma j$ (5×10^{-8} events). Multiple events in the same beam crossing [19] or the overlap of a cosmic ray interaction with a $\bar{p}p$ event contribute a total of 8×10^{-9} events. We emphasize that while these SM estimates are small and have led to valuable speculation [1], it is indefensible to claim evidence of new physics based on one peculiar event selected from 3×10^{12} events.

One possible source of an $ee\gamma\gamma\cancel{E}_T$ signature is anomalous $WW\gamma\gamma$ production. This hypothesis can be checked by searching for events where each W decayed hadronically rather than leptonically. A Monte Carlo study using a standard model $WW\gamma\gamma$ calculation [20] shows that anomalous $WW\gamma\gamma$ production would produce detected events with two photons with $E_T > 25$ GeV and three or more jets 30 times more often than events with two photons, two leptons and \cancel{E}_T . No events with three or more jets are seen in the N_{jet} distribution (Figure 1d).

We proceed to set limits on two SUSY models. There has been recent interest in supersymmetric models with either the lightest neutralino (N_1) decaying into a photon and gravitino (\tilde{G}) [1b, 1c, 1e, 1g], $N_1 \rightarrow \gamma\tilde{G}$, or a supergravity scenario in which the second-lightest neutralino decays via a loop into the lightest neutralino and a photon [1c], $N_2 \rightarrow \gamma N_1$. Both of these models would produce events with two photons and \cancel{E}_T .

We use the SPYTHIA Monte Carlo [21] with a full detector simulation to investigate the $N_2 \rightarrow \gamma N_1$ model of Ambrosanio *et al.* with $M_{N_1} = 36.6$ GeV and $M_{N_2} = 64.6$ GeV [22]. Direct production and cascade decays are predicted to produce 2.4 events that pass the selection criteria of $E_T^\gamma > 12$ GeV and $\cancel{E}_T > 35$ GeV. In the data only the one event passes this selection; we consequently cannot exclude this model. To provide a normalization point (*e.g.* for model-builders to estimate the detector efficiency), we have simulated direct $N_2 N_2$ production for this same model and find an acceptance of 5.4%. Treating the one event as signal, and performing no background subtraction, we derive a 95% C.L. cross section upper

limit of 1.1 pb.

Production of $\gamma\gamma$ events in the light gravitino scenario of Babu *et al.* [1]e is dominated by $C_1 N_2$ and $C_1 C_1$ production and decay. Figure 2 shows the cross-section limits, using the same methods, versus the mass of the C_1 . The lines show the experimental limit and the theoretically predicted cross section for the lowest value of M_{C_1} that is excluded ($M_{C_1} < 120$ GeV at 95% C.L., for $\tan\beta = 5$, $\mu < 0$). Note that because the C_1 and N_1 masses are related we also exclude $M_{N_1} < 65$ GeV at 95% C.L. ($\mu > 0$, $\tan\beta = 5$). These limits are similar to those of the DØ collaboration [23].

In conclusion, we have searched a sample of 85 pb^{-1} for events with two central photons and anomalous production of missing transverse energy, jets, charged leptons (e , μ , and τ), b -quarks and photons. We find good agreement with standard model expectations, with the possible exception of one event which has unusually large \cancel{E}_T and in addition to the two photons has a high- E_T central electron and a high- E_T electromagnetic cluster.

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- [10] The fiducial region is defined to be $0.05 < |\eta| < 1.0$, $0 < \phi < 2\pi$ with 86.7% coverage

for the high-threshold trigger. For the low-threshold trigger, the coverage is reduced to 73.3%.

- [11] For events in which either photon has $E_T < 22$ GeV the isolation requirement is that a 3-by-3 array of trigger-towers around the photon cluster contain less than 4 GeV. Isolation for events with both photons with $E_T > 22$ GeV is defined as the ratio of the energy in a cone of 0.4 in $\eta - \phi$ space, minus the photon cluster energy, over the cluster energy. We require Isolation < 0.1 . In addition we require that the sum of the P_T of the tracks in the cone be less than 5 GeV, and the cluster energy in the hadronic calorimeter divided by that in the electromagnetic be less than $0.055 + 0.00045E(\text{GeV})$.
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TABLES

Signature (Object)	Obs.	Expected	Ref.
$\cancel{E}_T > 35 \text{ GeV}, \Delta\phi_{\cancel{E}_T\text{-jet}} > 10^\circ$	1	0.5 ± 0.1	–
$N_{\text{jet}} \geq 4, E_T^{\text{jet}} > 10 \text{ GeV}, \eta^{\text{jet}} < 2.0$	2	1.6 ± 0.4	[15]
$b\text{-tag}, E_T^b > 25 \text{ GeV}$	2	1.3 ± 0.7	[15]
Central $\gamma, E_T^{\gamma_3} > 25 \text{ GeV}$	0	0.1 ± 0.1	–
Central e or $\mu, E_T^e \text{ or } \mu > 25 \text{ GeV}$	3	0.3 ± 0.1	[15]
Central $\tau, E_T^\tau > 25 \text{ GeV}$	1	0.2 ± 0.1	[16]

TABLE I. Number of observed and expected $\gamma\gamma$ events with additional objects in 85 pb^{-1} . The selection criteria, efficiencies, and background estimation methods used in identifying the jets, leptons and b -tags are discussed in the references.

	P_x	P_y	P_z	E	E_T
	(GeV/c)	(GeV/c)	(GeV/c)	(GeV)	(GeV)
γ_1	32.1(9)	-16.8(5)	-35(1)	50(1)	36(1)
γ_2	-12.9(4)	-29.6(9)	-22.5(7)	39(1)	32.3(9)
e^-	-34(1)	11.5(3)	21.7(6)	42(1)	36(1)
Plug EM Cluster	60(2)	19.0(5)	-172(5)	183(5)	63(2)
\cancel{E}_T	-54(7)	13(7)	—	—	55(7)

TABLE II. The 4-vectors of the objects in the $ee\gamma\gamma\cancel{E}_T$ candidate event. The parentheses represent the uncertainty in the last digit. There are no jets with $E_T > 10 \text{ GeV}$.

FIGURES

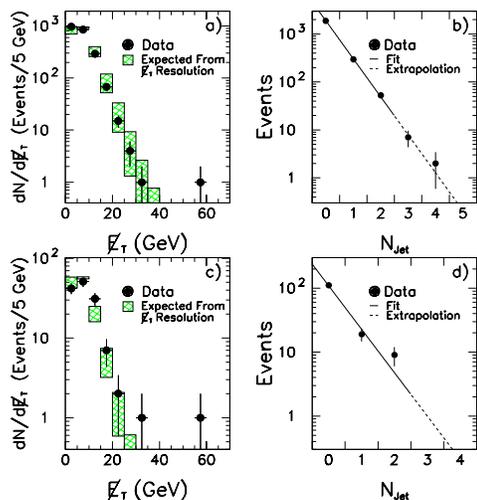


FIG. 1. a) The \cancel{E}_T spectrum for events with two central photons with $E_T > 12$ GeV. We have removed events which have any jet with $E_T > 10$ GeV pointing within 10 degrees in azimuth of the \cancel{E}_T . The cross-hatched regions represent the background estimates derived from the \cancel{E}_T resolution in the Z^0 control sample. b) The spectrum in number of jets with $E_T > 10$ GeV and $|\eta| < 2.0$ (N_{jet}) for events with two central photons with $E_T > 12$ GeV. c) and d) the same plots with photon $E_T > 25$ GeV.

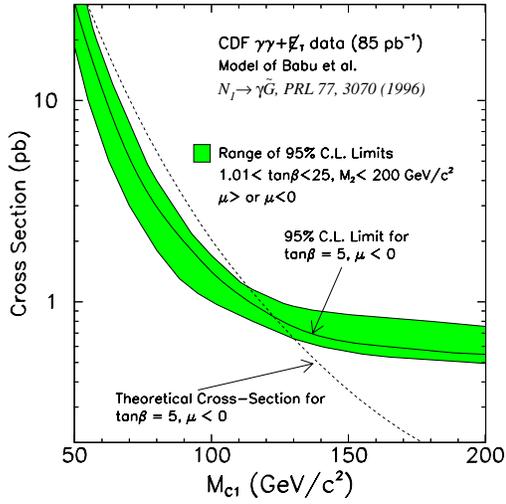


FIG. 2. The cross-section upper limits versus the mass of the C_1 for the light gravitino scenario of Babu *et al.* [1]e. The shaded region shows the range of cross section limits as the parameters are varied within the ranges $1 < \tan\beta < 25$, $M_2 < 200 \text{ GeV}$, and $\mu > 0$ or $\mu < 0$. The lines show the experimental limit and the theoretically predicted cross section for the lowest value of M_{C_1} that is excluded ($M_{C_1} < 120 \text{ GeV}$ at 95% C.L., for $\tan\beta = 5$, $\mu < 0$).