Search for New Physics in Lepton + Photon + X Events with 305 pb^{-1} of $p\bar{p}$ Collisions at $\sqrt{s}$ = 1.96 TeV

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We present results of a search for anomalous production of events containing a charged lepton (ℓ, either e or μ) and a photon (γ), both with high transverse momentum, accompanied by additional signatures X, including missing transverse energy ($\not{E}_T$) and additional leptons and photons. We use the same selection criteria as in a previous CDF search but with a substantially larger data set, 305 pb^{-1}, a $p\bar{p}$ collision energy of 1.96 TeV, and the CDF II detector. We find 42 $\ell\gamma\not{E}_T$ events versus an expectation of 37.3 ± 5.4 events. We observe 31 $\ell\ell\gamma + X$ events versus an expectation of 23.0 ± 2.7 events. We find no events similar to the run I $ee\gamma\gamma\not{E}_T$ event.

In 1995, the CDF experiment, studying $p\bar{p}$ collisions in 86 pb^{-1} of data at a center-of-mass energy of 1.8 TeV at the Fermilab Tevatron, observed [1] an event consistent with the production of two energetic photons, two energetic electrons, and large missing transverse energy $\not{E}_T$ [2]. This signature is predicted to be very rare in the standard model (SM) of particle physics [4], with the dominant contribution being from the production of four gauge bosons: two W bosons and two photons. The event raised theoretical interest, however, as the $\ell\ell\gamma\gamma$ signature is expected in some models of physics "beyond the standard model" such as gauge-mediated models of supersymmetry [5] or the production of a pair of excited electrons [6]. The detection of this event led to the development of

"signature-based" inclusive searches to cast a wider net for new phenomena: in this case, one search for two photons + X ($\gamma\gamma + X$) [1] and a second for one lepton + one photon + X ($\ell\gamma + X$) [7–9], where X can be e, μ, γ, or $\not{E}_T$, plus any number of jets.

Neither run I search revealed convincing evidence for new physics. However, in the $\ell\gamma + X$ search, the results were consistent with SM expectations, with "the possible exception of photon-lepton events with large $\not{E}_T$, for which the observed total was 16 events and the SM expectation was 7.6 ± 0.7 events, corresponding in likelihood to a 2.7 sigma effect." [8]. The run I paper concluded: "However, an excess of events with 0.7% likelihood (equivalent to 2.7 standard deviations for a Gaussian distribution) in one subsample among the five studied is an interesting result, but it is not a compelling observation of new physics. We look forward to more data in the upcoming run of the Fermilab Tevatron." [8]. In this Letter, we report the results of repeating the $\ell\gamma + X$ search with the same kinematic selection criteria in a substantially larger data set 305 ± 18 pb^{-1}, a higher $p\bar{p}$ collision energy 1.96 TeV, and the CDF II detector [10].

The CDF I detector is a cylindrically symmetric spectrometer designed to study $p\bar{p}$ collisions at the Fermilab Tevatron based on the same solenoidal magnet and central calorimeters as the CDF I detector [11] from which it was upgraded. Because the analysis described here is intended to repeat the run I search as closely as possible, we note especially the differences from the CDF I detector relevant to the detection of leptons, photons, and $\not{E}_T$. The tracking systems used to measure the momenta of charged particles have been replaced with a central outer tracker (COT), with smaller drift cells [12], and an enhanced system of silicon strip detectors [13]. The calorimeters in the regions [3] with pseudorapidity $|\eta| > 1$ have been replaced with a more compact scintillator-based design, retaining the projective geometry [14]. The coverage in φ of the CMP and CMX muon systems [15] has been extended; the CMU system is unchanged [10].

A 3-level trigger [10] system selects events with a high transverse momentum (p_T) [2] lepton ($p_T > 18$ GeV) or photon ($E_T > 25$ GeV) in the central region $|\eta| \lesssim 1.0$. The trigger system selects photon and electron candidates from clusters of energy in the central electromagnetic calorimeter. Electrons are distinguished from photons by requiring a COT track pointing at the cluster. The muon trigger requires a COT track that extrapolates to a track segment ("stub") in the muon chambers.

Inclusive $\ell\gamma$ events are selected by requiring a central γ candidate with $E_T^\gamma > 25$ GeV and a central e or μ with $E_T^\ell > 25$ GeV originating less than 60 cm along the beam line from the detector center and passing the "tight" criteria listed below.

The identification of leptons and photons is essentially the same as in the run I search [7]. A muon candidate

passing the tight cuts must have (a) a well-measured track in the COT; (b) energy deposited in the calorimeter consistent with expectations; (c) a muon stub in both the CMU and CMP, or in the CMX, consistent with the extrapolated COT track; and (d) COT timing consistent with a track from a $p\bar{p}$ collision. An electron candidate passing the tight selection must have (a) a high-quality track with $p_T > 0.5E_T$, unless $E_T > 100$ GeV, in which case the p_T threshold is set to 25 GeV; (b) a good transverse shower profile that matches the extrapolated track position; (c) a lateral sharing of energy in the two calorimeter towers containing the electron shower consistent with that expected; and (d) minimal leakage into the hadron calorimeter [16].

Photon candidates are required to have no track with $p_T > 1$ GeV and at most one track with $p_T < 1$ GeV, pointing at the calorimeter cluster, good profiles in both transverse dimensions at shower maximum, and minimal leakage into the hadron calorimeter [16].

To reduce background from photons or leptons from the decays of hadrons produced in jets, both the photon and the lepton in each event are required to be "isolated." The E_T deposited in the calorimeter towers in a cone in $\eta - \varphi$ space [3] of radius $R = 0.4$ around the photon or lepton position is summed, and the E_T due to the photon or lepton is subtracted. The remaining E_T is required to be less than 2.0 GeV $+ 0.02 \times (E_T - 20$ GeV) for a photon or less than 10% of the E_T for electrons or p_T for muons. In addition, for photons the sum of the p_T of all tracks in the cone must be less than 2.0 GeV $+ 0.005 \times E_T$.

Missing transverse energy $\not{E}_T$ is calculated from the calorimeter tower energies in the region $|\eta| < 3.6$. Corrections are then made to the $\not{E}_T$ for nonuniform calorimeter response [17] for jets with uncorrected $E_T > 15$ GeV and $\eta < 2.0$ and for muons with $p_T > 20$ GeV.

A total of 574 events, 508 inclusive $e\gamma$ and 66 inclusive $\mu\gamma$ candidates, pass the $\ell\gamma$ selection criteria. Of the 508 inclusive $e\gamma$ events, 397 have the electron and photon within 30° of back to back in φ, $\not{E}_T < 25$ GeV, and no additional leptons or photons. These are dominated by $Z^0 \rightarrow e^+e^-$ decays, in which one of the electrons radiates a high-E_T photon while traversing the material inside the COT active volume, leading to the observation of an electron and a photon approximately back to back in φ, with an $e\gamma$ invariant mass close to the Z^0 mass.

We use $W^\pm$ and Z^0 production as control samples to ensure that the efficiencies for high-p_T electrons and muons, as well as for $\not{E}_T$, are well understood. The photon control sample is constructed from events in which one of the electrons radiates a high-E_T γ such that the $e\gamma$ invariant mass is within 10 GeV of the Z^0 mass.

The first search we perform is in the $\ell\gamma\not{E}_T + X$ subsample, defined by requiring that an event contain $\not{E}_T > 25$ GeV in addition to the γ and tight lepton. Of the 574 $\ell\gamma$ events, 25 $e\gamma\not{E}_T$ events and 17 $\mu\gamma\not{E}_T$ events pass the $\not{E}_T$ requirement. Figure 1 shows the observed distributions in
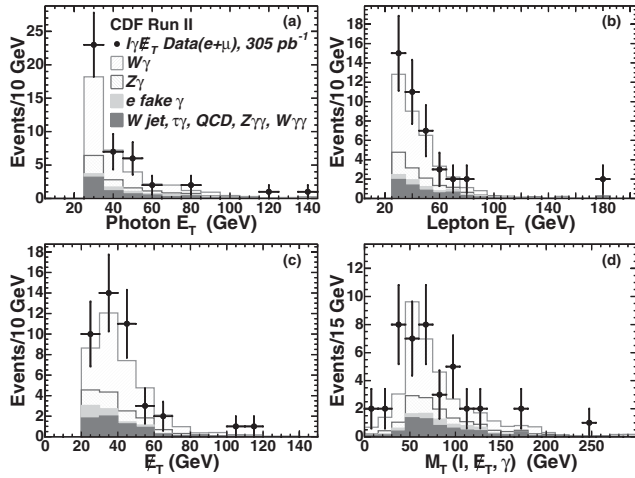
FIG. 1.   The distributions for events in the $\ell\gamma\slashed{E}_T$ sample (points) in (a) the $\slashed{E}_T$ of the photon; (b) the E_T of the lepton; (c) the missing transverse energy $\slashed{E}_T$; and (d) the transverse mass of the $\ell\gamma\slashed{E}_T$ system. The histograms show the expected SM contributions, including estimated backgrounds from misidentified photons and leptons.

1(a) the E_T of the photon; 1(b) the E_T of the lepton; 1(c) $\slashed{E}_T$; and 1(d) the transverse mass of the $\ell\gamma\slashed{E}_T$ system, where $M_T = [(E_T^\ell + E_T^\gamma + \slashed{E}_T)^2 - (\vec{E}_T^\ell + \vec{E}_T^\gamma + \vec{\slashed{E}}_T)^2]^{1/2}$.

A second search, for the $\ell\ell\gamma + X$ signature, is constructed by requiring another e or μ in addition to the tight lepton and the γ. The additional muons are required to have $p_T > 20$ GeV and to satisfy the same criteria as for tight muons but with fewer hits required on the track, or, alternatively, a more stringent cut on track quality but no requirement that there be a matching stub in the muon systems. Additional central electrons are required to have
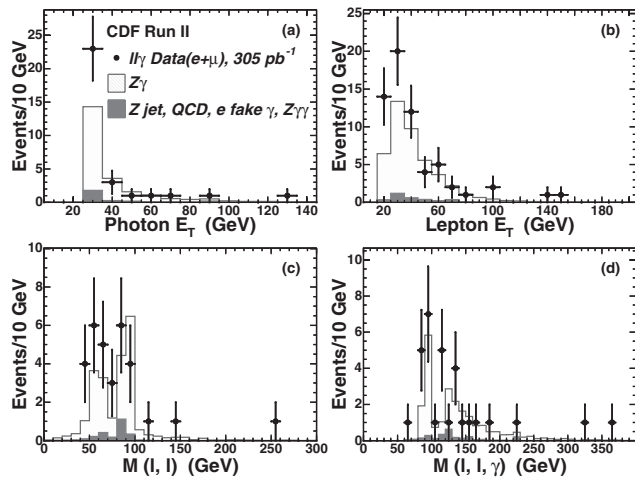

FIG. 2.   The distributions for events in the $\ell\ell\gamma$ sample (points) in (a) the E_T of the photon; (b) the E_T of the leptons (two entries per event); (c) the 2-body mass of the dilepton system; and (d) the 3-body mass $m_{\ell\ell\gamma}$. The histograms show the expected SM contributions.

$E_T > 20$ GeV and to satisfy the tight central electron criteria but with a track requirement of only $p_T > 10$ GeV (rather than $0.5 \times E_T$) and no requirement on a shower maximum measurement or lateral energy sharing between calorimeter towers. Electrons in the end-plug calorimeters ($1.2 < |\eta| < 2.0$) are required to have $E_T > 15$ GeV, minimal leakage into the hadron calorimeter, a "track" containing at least 3 hits in the silicon tracking system, and a shower transverse shape consistent with that expected, with a centroid close to the extrapolated position of the track [18].

The $\ell\ell\gamma$ search criteria select 31 events (19 $ee\gamma$ and 12 $\mu\mu\gamma$) of the 574 $\ell\gamma$ events. No $e\mu\gamma$ events are observed. Figure 2 shows the observed distributions in 2(a) the E_T of the photon; 2(b) the E_T of the leptons; 2(c) the 2-body mass of the dilepton system; and 2(d) the 3-body mass $m_{\ell\ell\gamma}$.

We do not expect SM events with large $\slashed{E}_T$ in the $\ell\ell\gamma$ sample; the run I $ee\gamma\gamma\slashed{E}_T$ event was of special interest in the context of supersymmetry [5] due to the large value of $\slashed{E}_T$ (55 ± 7 GeV). Figure 3 shows the distributions in $\slashed{E}_T$ for the $\mu\mu\gamma$ and $ee\gamma$ subsamples of the $\ell\ell\gamma$ sample. No events are observed with $\slashed{E}_T > 25$ GeV.

The dominant SM source of $\ell\gamma$ events is electroweak W and Z^0/γ^* production along with a γ radiated from one of the charged particles involved in the process [19]. The number of such events is estimated using leading-order event generators [20–22]. Initial state radiation is simulated by the PYTHIA shower Monte Carlo (MC) code [23] tuned to reproduce the underlying event. The generated particles are then passed through a full detector simulation, and these events are then reconstructed with the same code used for the data.

The expected contributions from $W\gamma$ and $Z^0/\gamma^* + \gamma$ production to the $\ell\gamma\slashed{E}_T$ and $\ell\ell\gamma$ searches are given in Table I. A correction for higher-order processes (K factor) has been applied [24]. In the $\ell\gamma\slashed{E}_T$ signature, we expect 22.5 ± 2.8 events from $W\gamma$ and 5.7 ± 1.0 from $Z^0/\gamma^* + \gamma$. In the $\ell\ell\gamma$ signature, we expect 20.3 ± 2.4 events from $Z^0/\gamma^* + \gamma$; the contribution from $W\gamma$ is negligible. The uncertainties on the SM contributions include those from parton distribution functions (5%), factorization scale
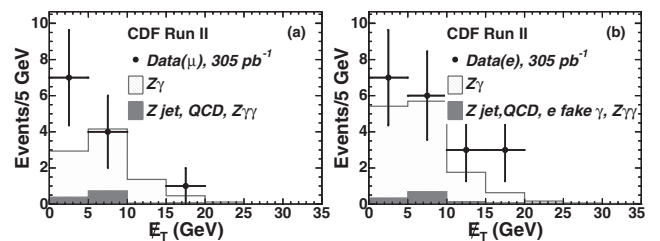

FIG. 3.   The distributions in missing transverse energy $\slashed{E}_T$ observed in the inclusive search for (a) $\mu\mu\gamma$ events and (b) $ee\gamma$ events. The histograms show the expected SM contributions.

TABLE I. A comparison of the numbers of events predicted by the SM and the observations for the $\ell\gamma\not{E}_T$ and $\ell\ell\gamma$ searches. The SM predictions are dominated by $W\gamma$ and $Z^0\gamma$ production, respectively [20–22]. Other contributions come from $W\gamma\gamma$ and $Z^0\gamma\gamma$, leptonic τ decays, and misidentified leptons, photons, or $\not{E}_T$.

	Lepton + photon + $\not{E}_T$ events		
SM source	$e\gamma\not{E}_T$	$\mu\gamma\not{E}_T$	$(e+\mu)\gamma\not{E}_T$
$W^{\pm}\gamma$	13.70 ± 1.89	8.84 ± 1.35	22.54 ± 2.80
$Z^0/\gamma^* + \gamma$	1.16 ± 0.40	4.49 ± 0.64	5.65 ± 1.03
$W^{\pm}\gamma\gamma, Z^0/\gamma^* + \gamma\gamma$	0.14 ± 0.02	0.18 ± 0.02	0.32 ± 0.03
$W^{\pm}\gamma, Z^0/\gamma^* + \gamma \to \tau\gamma$	0.71 ± 0.18	0.26 ± 0.08	0.97 ± 0.22
$W^{\pm} + $ jet faking γ	2.8 ± 2.8	1.6 ± 1.6	4.4 ± 4.4
$Z^0/\gamma^* \to e^+e^-, e \to \gamma$	2.45 ± 0.33	$\cdots$	2.45 ± 0.33
Jets faking $\ell + \not{E}_T$	0.7 ± 0.7	0.3 ± 0.3	1.0 ± 0.8
Total	21.7 ± 3.4	15.7 ± 2.2	37.3 ± 5.4
Observed	25	17	42
	Multilepton + photon events		
SM source	$ee\gamma$	$\mu\mu\gamma$	$ll\gamma$
$Z^0/\gamma^* + \gamma$	12.50 ± 1.53	7.81 ± 0.88	20.31 ± 2.40
$Z^0/\gamma^* + \gamma\gamma$	0.24 ± 0.03	0.12 ± 0.02	0.36 ± 0.04
$Z^0/\gamma^* + $ jet faking γ	0.3 ± 0.3	0.2 ± 0.2	0.5 ± 0.5
$Z^0/\gamma^* \to e^+e^-, e \to \gamma$	0.23 ± 0.09	$\cdots$	0.23 ± 0.09
Jets faking $\ell + \not{E}_T$	0.6 ± 0.6	1.0 ± 1.0	1.6 ± 1.2
Total	13.9 ± 1.7	9.1 ± 1.4	23.0 ± 2.7
Observed	19	12	31

(2%), and K factor (3%), a comparison of different MC generators ($\sim 5\%$), and the luminosity (6%).

High p_T photons are copiously created from hadron decays in jets initiated by a scattered quark or gluon. In particular, mesons such as the π^0 or η decay to photons which may satisfy the photon selection criteria. The numbers of lepton-plus-misidentified-jet events expected in the $\ell\gamma\not{E}_T$ and $\ell\ell\gamma$ samples are determined by measuring the jet E_T spectrum in $\ell\not{E}_T + $ jet and $\ell\ell + $ jet samples, respectively, and then multiplying by the probability of a jet being misidentified as a photon, $P_\gamma^{\text{jet}}(E_T)$, which is measured in data samples triggered on jets. The misidentification rate is $P_\gamma^{\text{jet}} = (6.5 \pm 3.3) \times 10^{-4}$ for $E_T^\gamma = 25$ GeV and $(4.0 \pm 4.0) \times 10^{-4}$ for $E_T^\gamma = 50$ GeV [19]. The predicted number of events with jets misidentified as photons is 4.4 ± 4.4 for the $\ell\gamma\not{E}_T$ signature and 0.5 ± 0.5 for $\ell\ell\gamma$.

The probability that an electron undergoes hard bremsstrahlung and is misidentified as a photon, P_γ^e, is measured from the photon control sample. The number of misidentified $e\gamma$ events divided by twice the number of ee events gives $P_\gamma^e = (1.7 \pm 0.1)\%$. Applying this misidentification rate to electrons in the inclusive lepton samples, we find 2.5 ± 0.3 and 0.2 ± 0.1 events pass the selection criteria for the $\ell\gamma\not{E}_T$ and $\ell\ell\gamma$ searches, respectively.

We have estimated the background due to events with jets misidentified as $\ell\gamma\not{E}_T$ or $\ell\ell\gamma$ signatures by studying the total p_T of tracks in a cone in $\eta - \varphi$ space of radius $R = 0.4$ around the lepton track. We estimate there are

1.0 ± 0.8 and 1.6 ± 1.2 events in the $\ell\gamma\not{E}_T$ and $\ell\ell\gamma$ signatures, respectively.

We have used both MADGRAPH [20] and COMPHEP [22] to simulate the triboson channels $W\gamma\gamma$ and $Z\gamma\gamma$. The expected contributions are small: 0.32 ± 0.03 and 0.36 ± 0.04 events in the $\ell\gamma\not{E}_T$ and $\ell\ell\gamma$ signatures, respectively.

Muon backgrounds from hadrons either decaying in flight or penetrating the iron before the muon chambers, and from the decay of bottom and charm quarks, are found to be negligible.

The predicted and observed totals for both the $\ell\gamma\not{E}_T$ and $\ell\ell\gamma$ searches are shown in Table I. We observe 42 $\ell\gamma\not{E}_T$ events, versus the expectation of 37.3 ± 5.4 events. In the $\ell\ell\gamma$ channel, we observe 31 events, versus an expectation of 23.0 ± 2.7 events. There is no significant excess in either signature. The predicted and observed kinematic distributions are compared in Fig. 1 for the $\ell\gamma\not{E}_T$ signature and in Figs. 2 and 3 for the $\ell\ell\gamma$ search.

In conclusion, we have repeated the search for inclusive lepton + photon production with the same kinematic requirements as the run I search, but with a significantly larger data sample and a higher collision energy. We find that the numbers of events in the $\ell\gamma\not{E}_T$ and $\ell\ell\gamma$ subsamples of the $\ell\gamma + X$ sample agree with SM predictions. We observe no $\ell\ell\gamma$ events with anomalous large $\not{E}_T$ or with multiple photons and so find no events such as the $ee\gamma\gamma\not{E}_T$ event of run I.

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[2] Transverse momentum and energy are defined as $p_T = p \sin\theta$ and $E_T = E \sin\theta$, respectively. Missing E_T ($\vec{\not{E}}_T$) is defined by $\vec{\not{E}}_T = -\sum_i E_T^i \hat{n}_i$, where i is the calorimeter tower number for $|\eta| < 3.6$ (see Ref. [3]), and $\hat{n}_i$ is a unit vector perpendicular to the beam axis and pointing at the ith tower. We correct $\vec{\not{E}}_T$ for jets and muons. We define the magnitude $\not{E}_T = |\vec{\not{E}}_T|$. We use the convention that "momentum" refers to pc and "mass" to mc^2.

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[16] The fraction of electromagnetic energy allowed to leak into the hadron compartment $E_{\mathrm{had}}/E_{\mathrm{em}}$ must be less than $0.055 + 0.00045 \times E_{\mathrm{em}}$ (GeV) for central electrons, less than 0.05 for electrons in the end-plug calorimeters, and less than $\max[0.125, 0.055 + 0.00045 \times E_{\mathrm{em}}$ (GeV)] for photons.

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