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We compare the inclusive production of events containing a lepton (ℓ), a photon (γ), significant transverse momentum imbalance ($\not\!\!E_T$), and a jet identified as containing a b-quark, to SM predictions. The search uses data produced in proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV corresponding to 1.9 fb^{-1} of integrated luminosity taken with the CDF detector. We find 28 $\ell\gamma b\not\!\!E_T$ events versus an expectation of $31.0^{+4.1}_{-3.5}$ events. If we further require events to contain at least three jets and large total transverse energy, the largest SM source is radiative top-quark pair production, $t\bar{t} + \gamma$. In the data we observe 16 $t\bar{t}\gamma$ candidate events versus an expectation from SM sources of $11.2^{+2.3}_{-2.1}$. Assuming the difference between the observed number and the predicted non-top-quark total of $6.8^{+2.2}_{-2.0}$ is due to SM top-quark production, we estimate the $t\bar{t}\gamma$ cross section to be 0.15 ± 0.08 pb.

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The unknown nature of possible new phenomena in the energy range accessible at the Tevatron collider is the motivation for a search strategy [1–3] that does not focus on current hypothetical models of new physics, but instead tests the standard model (SM) [4]. The emphasis on presenting measurements and SM predictions, rather than comparisons with arbitrarily chosen other models, allows a wide net for physics beyond the SM that can be used now by proponents of current models of ''new physics'' as well as in the future by theorists with new ideas and facts. Here we report the results of a search for events containing a lepton (ℓ), a photon (γ), significant transverse momentum imbalance ($\not\!\!E_T$) [5], and a jet identified as containing a b-quark; i.e. the final-state $\ell\gamma b\not\!\!E_T + X$. This channel, which contains a vector boson and a third-generation quark, is suppressed in the SM, and is consequently sensitive to rare new phenomena. The data correspond to an integrated luminosity of 1.9 fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, collected using the CDF II detector [7]. This search is an extension of a previous search in the lepton + photon + X signature, described in detail in Ref. [8].

A search for SM production of top-quark pairs with an additional photon, $t\bar{t}\gamma$, is a natural extension of the $\ell\gamma b\not\!\!E_T + X$ analysis. By further requiring events to contain at least three jets and large total transverse energy (H_T) [5], we find that the SM predicts the largest source of events will be top-quark pair production with an additional radiated photon, $t\bar{t} + \gamma$. The process is of interest for the direct measurement of the electric charge of the top quark [9], as well as being another low-cross section search signature in which rare non-SM processes could appear.

The CDF II detector [7] is a cylindrically-symmetric magnetic spectrometer designed to study $p\bar{p}$ collisions at the Fermilab Tevatron. Here we briefly describe the detector subsystems relevant for the present analysis.

Tracking systems are used to measure the momenta of charged particles and to identify leptons with large transverse momenta [5]. A multilayer system of silicon strip detectors [10], which identifies tracks in both the $r - \phi$ and $r - z$ views [6], and the central outer tracker (COT) [11], are contained in a superconducting solenoid that generates a magnetic field of 1.4 T. The COT is a 3.1 m long open-cell drift chamber that makes up to 96 measurements along the track of each charged particle in the region $|\eta| < 1$. Sense wires are arranged in 8 alternating axial and $\pm 2°$ stereo superlayers with 12 wire layers each. For high-momentum tracks, the COT transverse momentum (p_T) resolution is $\sigma_{p_T}/p_T^2 \simeq 0.0017$ GeV^{-1} [11].

Segmented calorimeters with towers arranged in a projective geometry, each tower consisting of an electromagnetic and an hadronic compartment [12,13], cover the region $|\eta| < 3.6$. In this analysis we select photons and electrons in the central region, $|\eta| < 1$, where a system (CES) with finer spatial resolution is used to make profile measurements of electromagnetic showers at shower maximum [7]. Electrons are reconstructed in the central electromagnetic calorimeter (CEM) with an E_T resolution of $\sigma(E_T)/E_T \simeq 13.5\%/\sqrt{E_T/\mathrm{GeV}} \oplus 2\%$ [12]. Jets are identified in the electromagnetic and hadronic calorimeters using a cone in η-ϕ space of radius 0.4 [14,15]. The jet energy resolution is approximately $\sigma \simeq 0.1 \times E_T$ (GeV) + 1.0 GeV [16].

Muons are identified using the central muon (CMU), the central muon upgrade (CMP), and the central muon extension (CMX) systems [17,18], which cover the kinematic region $|\eta| < 1$. The CMU uses four layers of planar drift chambers to detect muons with $p_T > 1.4$ GeV in the region of $|\eta| < 0.6$. The CMP consists of four additional layers of planar drift chambers located behind 0.6 m of steel outside the magnetic return yoke, and detects muons with $p_T > 2.0$ GeV. The CMX detects muons in the region $0.6 < |\eta| < 1.0$ with four to eight layers of drift chambers, depending on the polar angle.

We use identification algorithms that exploit the long lifetime ($c\tau_0 \sim 450$ μm) of b hadrons to identify jets containing b hadrons. Candidate b-jets are identified through the presence of a secondary decay vertex displaced from the beam line in the region $|\eta| < 2$ [19].

The beam luminosity is measured using two arrays of gas Cherenkov counters, located in the region $3.7 < |\eta| < 4.7$. The total uncertainty on the luminosity has been estimated to be 6%, where 4.4% comes from the acceptance and operation of the luminosity monitor and 4.0% from the calculation of the accepted inelastic $p\bar{p}$ cross section [20].

We use events selected by the online event selection (trigger) system [7] to have a high p_T electron or muon in the central region, $|\eta| \lesssim 1.0$. The electron trigger requires a cluster of energy in the central electromagnetic calorimeter with a COT track pointing at the cluster. The muon trigger requires a COT track that extrapolates to a track segment in the muon chambers.

Inclusive $\ell\gamma$ events are selected by requiring a central high-energy γ candidate and a central high-energy e or μ candidate originating less than 60 cm along the beam line from the detector center and passing the selection criteria listed below. To reduce background from the decays of hadrons produced in jets, both the photon and the lepton in each event are required to be isolated [21].

An electron candidate must meet the following selection criteria: (a) a high-quality track [22] with $p_T > 0.5E_T$, unless $E_T > 100$ GeV, in which case the p_T threshold is set to 20 GeV; (b) a good transverse shower profile that matches the extrapolated track position; (c) a lateral sharing of energy in the calorimeter towers containing the electron shower consistent with that expected; and (d) minimal leakage into the hadron calorimeter [23].

A muon candidate must have: (a) a well-measured track in the COT; (b) energy deposited in the calorimeter consistent with expectations; (c) a muon track segment 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.

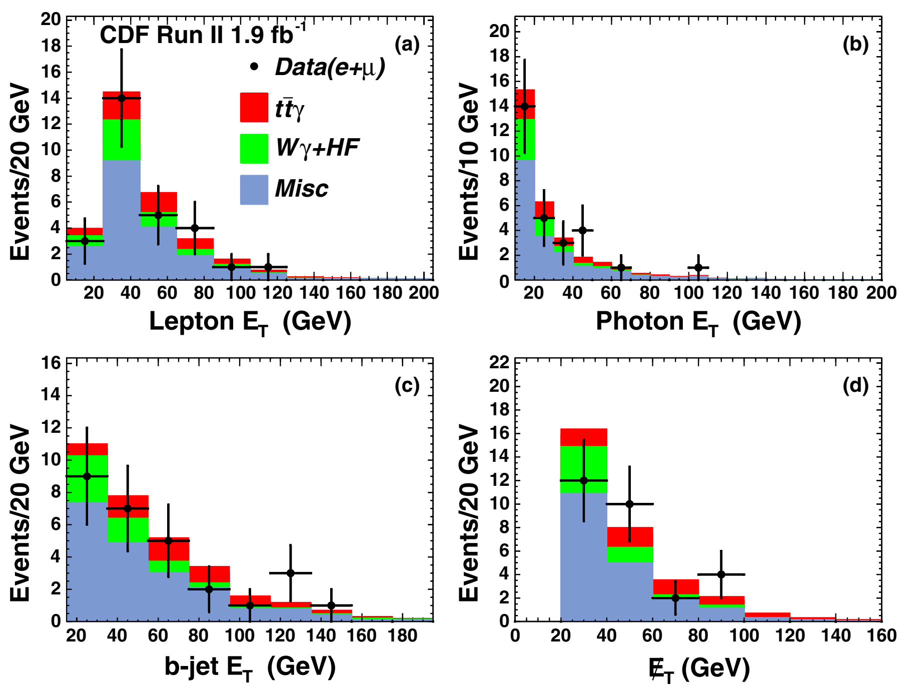

FIG. 1 (color online). The distributions for events in the $\ell\gamma b\not{E}_T$ sample (points) in (a) the E_T of the lepton; (b) the E_T of the photon; (c) the E_T of the most energetic b-jet in an event; and (d) the missing transverse energy. The histograms show the estimated SM contributions from radiative top quark decay ($t\bar{t}\gamma$), WZ production, $W\gamma$ production with heavy flavor (HF), τ leptons, electrons, and jets misidentified as photons, mistagged light-quark and gluon jets, and jets misidentified as leptons (QCD).

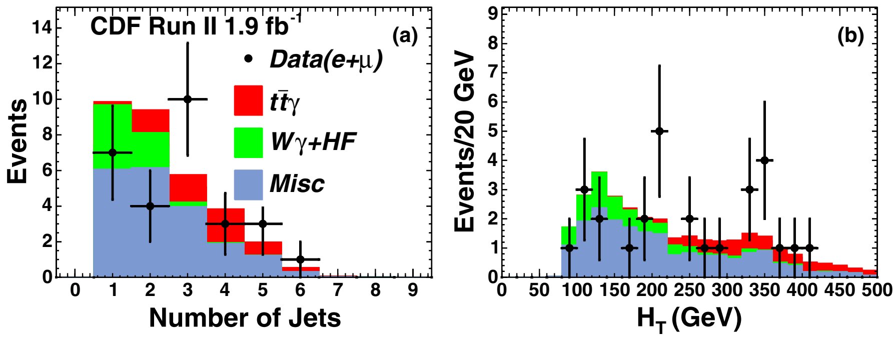

FIG. 2 (color online). The distributions for events in the $\ell\gamma b\not\!E_T$ sample (points) in (a) the total number of jets; (b) the total transverse energy H_T for the $\ell\gamma b\not\!E_T$ events. The histograms show the estimated SM contributions from radiative top-quark decay ($t\bar{t}\gamma$), WZ production, $W\gamma$ production with heavy flavor (HF), τ leptons, electrons, and jets misidentified as photons, mistagged light-quark and gluon jets, and jets misidentified as leptons (QCD).

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 [23].

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 the position of the reconstructed primary vertex, and for nonuniform calorimeter response [24] for jets with uncorrected $E_T >$ 15 GeV and $|\eta| < 2.0$, and for muons with $P_T^{\mu} > 20$ GeV.

The inclusive $\ell\gamma b\not\!E_T$ search is defined by requiring that an event contain a central electron (or muon) with $E_T^e(P_T^{\mu}) > 20$ GeV [5], a central photon with $E_T^{\gamma} >$ 10 GeV, a b-tagged jet with $E_T^{\rm jet} > 15$ GeV, and $\not\!E_T >$ 20 GeV [25]. Figures 1 and 2 show kinematic distributions for events in the $\ell\gamma b\not\!E_T$ sample.

The dominant SM sources of $\ell\gamma b\not\!E_T$ events at the Tevatron are $t\bar{t}\gamma$ production and $W\gamma$ + heavy flavor (HF) ($Wc\gamma$, $Wc\bar{c}\gamma$, $Wb\bar{b}\gamma$) in which a W boson decays leptonically ($\ell\nu$) and a photon is radiated from an initial-state quark, the W, or a charged final-state lepton [26]. We use the MADGRAPH matrix-element event generator [27] to estimate these contributions. Initial-state radiation and parton showering are simulated by the PYTHIA shower code [28] tuned to reproduce the underlying event [29]. The generated particles are then passed through a full simulation of the detector, and these events are then reconstructed with the same reconstruction code used for the data. The expected contributions from $t\bar{t}\gamma$ and $W\gamma$ + HF production to the $\ell\gamma b\not\!E_T$ and $t\bar{t}\gamma$ searches are given in Tables I and II. A correction for higher-order processes (K-factor) of 1.10 ± 0.15 for the $t\bar{t}\gamma$ [25] has been applied to the LO MC estimates. We have also applied a K-factor of 2.10 ± 1.05 for the $W\gamma$ + HF [30]. Backgrounds from WW, ZZ, and the production of a single top quark plus a photon are estimated to be negligible.

The background from top decays in which tau leptons are misidentified as photons is estimated from a $t\bar{t}$ PYTHIA [28] sample using simulation information to identify tau leptons and then applying the same analysis selection criteria as for data.

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 multiple photons which may pass the photon selection criteria. To estimate the number of events with a jet misidentified as a photon, we first measure the probability for a jet to be misidentified as a photon, $P_{\gamma}^{\rm jet}(E_T)$, as a function of the measured $E_T^{\rm jet}$, in data samples triggered on jets. We then measure the jet E_T in $\ell\not\!E_T b$ + jet and $\ell\not\!E_T$ + >3 jets ($H_T > 200$ GeV) samples, respectively, and multiply by $P_{\gamma}^{\rm jet}(E_T)$. An uncertainty of 50% on the number of such events is calculated by using the measured jet spectrum and the upper and lower bounds on the E_T-dependent misidentification rate [26].

TABLE I. Summary for the $\ell\gamma b\not\!E_T$ search. Backgrounds from WW, ZZ, and single top quark with an additional radiated photon are found to be negligible.

Lepton + Photon + $\not\!E_T$ + b Events SM Source	$e\gamma b\not\!E_T$	$\mu\gamma b\not\!E_T$	$(e+\mu)\gamma b\not\!E_T$
$t\bar{t}\gamma$ semileptonic	2.06 ± 0.38	1.52 ± 0.28	3.58 ± 0.65
$t\bar{t}\gamma$ dileptonic	1.30 ± 0.23	1.02 ± 0.18	2.32 ± 0.41
$W^{\pm}c\gamma$	1.58 ± 0.83	1.51 ± 0.80	3.09 ± 1.59
$W^{\pm}cc\gamma$	0.17 ± 0.12	0.46 ± 0.26	0.63 ± 0.35
$W^{\pm}bb\gamma$	1.30 ± 0.67	0.88 ± 0.46	2.18 ± 1.11
$Z(\tau\tau)\gamma$	0.13 ± 0.09	0.11 ± 0.08	0.24 ± 0.12
WZ	0.08 ± 0.04	0.01 ± 0.01	0.09 ± 0.04
$\tau \to \gamma$ fake	0.12 ± 0.04	0.10 ± 0.03	0.22 ± 0.05
Jet faking γ	4.56 ± 1.92	3.02 ± 1.19	7.58 ± 3.11
Mistagged b-jets	4.11 ± 0.41	3.54 ± 0.37	7.65 ± 0.70
QCD	1.5 ± 0.8	$0.0^{+1.0}_{-0.0}$	$1.5^{+1.3}_{-0.8}$
$ee\not\!E_T b$, $e \to \gamma$	1.50 ± 0.28	$\cdots$	1.50 ± 0.28
$\mu e\not\!E_T b$, $e \to \gamma$	$\cdots$	0.45 ± 0.10	0.45 ± 0.10
Predicted	18.4 ± 2.4(tot)	$12.6^{+1.9}_{-1.6}$(tot)	$31.0^{+4.1}_{-3.9}$(tot)
Observed	16	12	28

TABLE II. Summary of the expected SM contributions to the $t\bar{t}\gamma$ search. Backgrounds from WW, ZZ, single top quark with an additional radiated photon are found to be negligible.

$t\bar{t}\gamma$ SM Source	$e\gamma b\not{E}_T$	$\mu\gamma b\not{E}_T$	$(e+\mu)\gamma b\not{E}_T$
$t\bar{t}\gamma$ semileptonic	1.97 ± 0.36	1.47 ± 0.27	3.44 ± 0.62
$t\bar{t}\gamma$ dileptonic	0.52 ± 0.10	0.43 ± 0.08	0.95 ± 0.17
$W^{\pm}c\gamma$	$0.0^{+0.05}_{-0}$	$0.0^{+0.05}_{-0}$	$0^{+0.07}_{-0}$
$W^{\pm}cc\gamma$	$0.0^{+0.04}_{-0}$	0.03 ± 0.03	$0.03^{+0.05}_{-0.03}$
$W^{\pm}bb\gamma$	0.13 ± 0.08	0.02 ± 0.02	0.15 ± 0.09
WZ	0.02 ± 0.02	$0.0^{+0.02}_{-0}$	0.02 ± 0.02
$\tau \to \gamma$ fake	0.08 ± 0.01	0.02 ± 0.01	0.10 ± 0.01
Jet faking γ	2.37 ± 1.22	1.42 ± 0.70	3.79 ± 1.92
Mistagged b-jets	0.78 ± 0.20	0.83 ± 0.22	1.61 ± 0.31
QCD	0.5 ± 0.5	$0.0^{+1.0}_{-0.0}$	$0.5^{+1.1}_{-0.5}$
$ee\not{E}_T b$, $e \to \gamma$	0.34 ± 0.11	...	0.34 ± 0.11
$\mu e\not{E}_T b$, $e \to \gamma$	...	0.20 ± 0.06	0.20 ± 0.06
Predicted	6.7 ± 1.4(tot)	$4.4^{+1.3}_{-0.8}$(tot)	$11.2^{+2.3}_{-2.1}$(tot)
Observed	8	8	16

To estimate the probability to mistakenly b-tag a light jet (a mistag), each jet in the $\ell\gamma\not{E}_T$ + pretagged jet sample is weighted by its mistag rate that is obtained from tagged events in which the b-hadron decay vertex is measured to be on the opposite side of the primary vertex from the direction of the jet, an unphysical geometry. The mistag rate derived from these "negative" tags provides an estimate of the number of false positive tags after a correction for interactions in material in the inner tracking volume and long-lived light-flavor particles. The mistag rate per jet is measured using a large inclusive-jet data sample.

We have estimated the background due to events with jets misidentified as high-p_T leptons by studying the total p_T of tracks in a cone in η-φ space of radius $R = 0.4$ around the lepton track (track isolation) [8]. We compared the distribution of track isolation in the signal sample to that of the $Z^0 \to e^+e^-$ and $Z^0 \to \mu^+\mu^-$ data samples, and to that of the QCD background data sample, which is dominated by light-flavor and gluon jets.

The number of events with an electron misidentified as a photon expected in the $\ell\gamma b\not{E}_T$ sample is determined by measuring the electron E_T spectrum in $\ell e\not{E}_T b$ samples, and then multiplying by $P_{e\to\gamma}$, the probability of an electron being misidentified as a photon. We determine $P_{e\to\gamma}$ from $Z^0 \to e^+e^-$ events in which one of the electrons radiates a high-E_T photon, resulting in an electron-photon system with an invariant mass consistent with that of the Z-boson.

The uncertainties on the numbers of expected events for the $\ell\gamma b\not{E}_T$ search listed in Tables I and II include systematic and statistical uncertainties. A total uncertainty of 6% is quoted for the luminosity measurements [20]. The systematics relevant to the $\ell\gamma b\not{E}_T$ and $t\bar{t}\gamma$ analyses also include a 5% uncertainty on the b-tagging efficiency, and uncertainties on the K-factors of 15% for the $t\bar{t}\gamma$ MC samples and 50% for the $W\gamma$ + HF samples. The largest

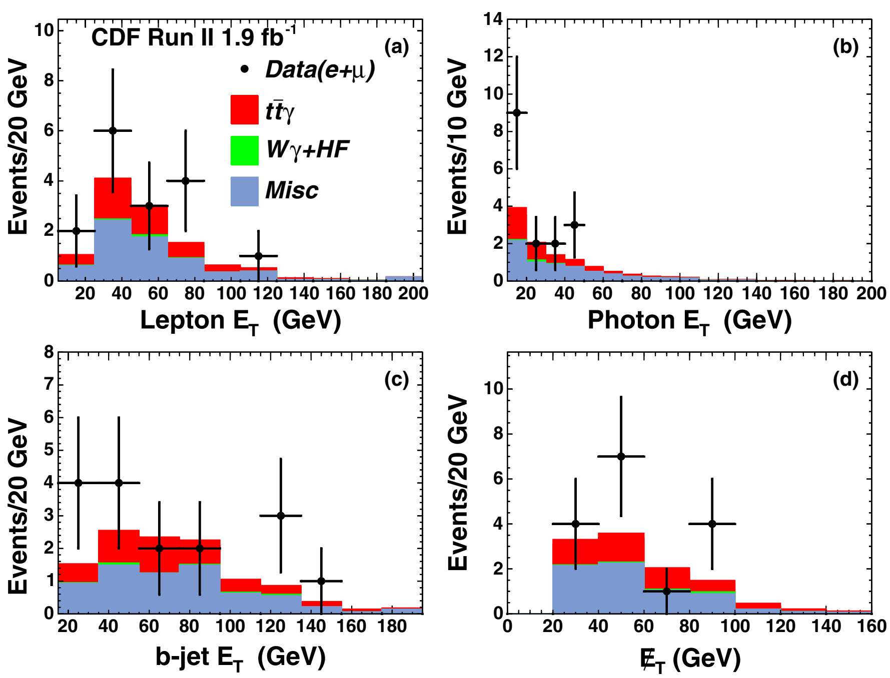

FIG. 3 (color online). The distributions for events in the $t\bar{t}\gamma$ sample (points) in (a) the E_T of the lepton; (b) the E_T of the photon; (c) the E_T of the most energetic b-jet in an event; and (d) the missing transverse energy, $\not{E}_T$. The histograms show the estimated SM contributions from radiative top-quark decay ($t\bar{t}\gamma$), WZ production, $W\gamma$ production with heavy flavor (HF), τ leptons, electrons, and jets misidentified as photons, mistagged light-quark and gluon jets, and jets misidentified as leptons (QCD).

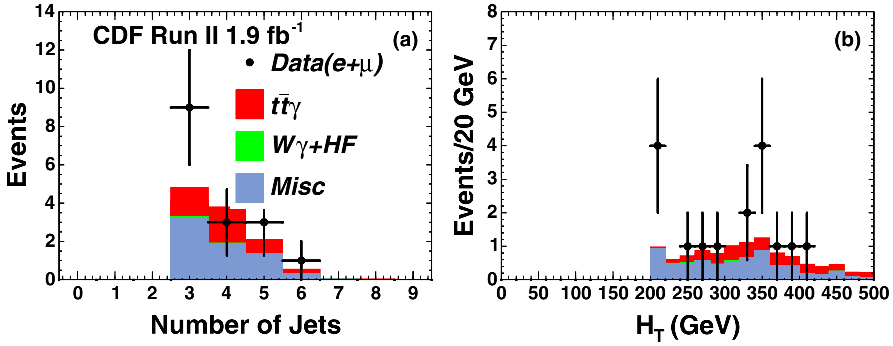

FIG. 4 (color online). The distributions for events in the $t\bar{t}\gamma$ sample (points) in (a) the total number of jets; (b) the total transverse energy H_T for the $\ell\gamma b\not{E}_T$ events. The histograms show the estimated SM contributions from radiative top-quark decay ($t\bar{t}\gamma$), WZ production, $W\gamma$ production with heavy flavor (HF), τ leptons, electrons, and jets misidentified as photons, mistagged light-quark and gluon jets, and jets misidentified as leptons (QCD).

experimental systematic uncertainty comes from the rate of misidentifying jets as photons, which we estimate to be uncertain to approximately 50%.

We find 28 $\ell\gamma b\not{E}_T$ events versus an expectation of $31.0^{+4.1}_{-3.5}$ events. The data agree well with the SM predictions, with the precision of the comparison being limited by statistics for the present integrated luminosity.

A second search, for $t\bar{t}\gamma$ events, is constructed by further requiring $H_T > 200$ GeV [31] and $N_{\rm jets} > 2$, where $N_{\rm jets}$ is the number of jets in the event [15]. We observe 16 $t\bar{t}\gamma$ candidate events. Figures 3 and 4 show the corresponding kinematic distributions for events in the $t\bar{t}\gamma$ subsample. An event display of a $t\bar{t}\gamma$ candidate event is shown in Fig. 5.

For the $t\bar{t}\gamma$ search, the detection efficiency and acceptance are calculated using MADGRAPH to generate $t\bar{t}\gamma$ events with one leptonic W decay. As in the $\ell\gamma b\not{E}_T$ search, the generated particles are then passed through a full detector simulation of the detector and are then reconstructed with the same reconstruction code used for the data. We find a SM expectation of $11.2^{+2.3}_{-2.1}$ events.

The probability that the backgrounds alone (i.e. assuming that there is no SM production of the $t\bar{t}\gamma$ final state) will produce 16 or more events, is 1% (2.3 standard deviations). Assuming that the difference between the nontop background estimate and the number of observed events is due to $t\bar{t}\gamma$ SM production, we estimate the $t\bar{t}\gamma$ cross section to be 0.15 ± 0.08 pb (see Fig. 6). An estimate of the expected semileptonic cross section $\sigma(\mathrm{SM}) = 0.080 \pm 0.011$ pb is obtained from the LO MADGRAPH cross section of 0.073 pb, multiplied by a K-factor ($\sigma_{\rm NLO}/\sigma_{\rm LO}$) of 1.10 ± 0.15 [25]. The uncertainty on the cross section is dominated by the statistical uncertainties associated with the small number of events observed.

In conclusion, we have performed a search for events containing a lepton, photon, b-quark production, and missing E_T, a channel which contains a vector boson and a third-generation quark and is suppressed in the SM. We find no evidence for non-SM production. As an extension

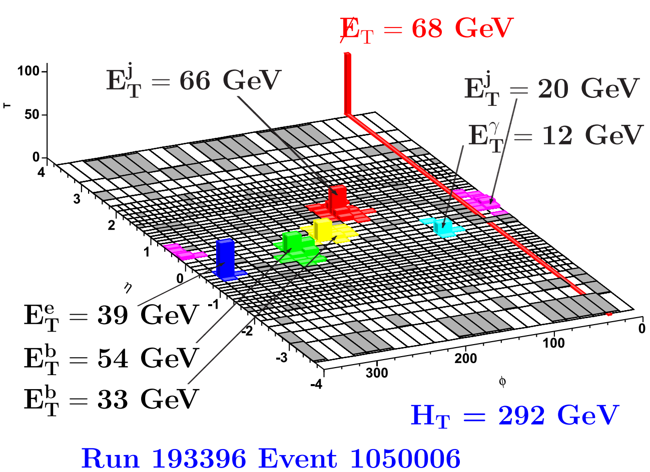

FIG. 5 (color online). The $\eta - \phi$ plot of a $t\bar{t}\gamma$ candidate event, in which the energies deposited in the calorimeter towers are displayed in the $\eta - \phi$ plane. The reconstructed top-quark mass is 167 GeV; the photon E_T is 12 GeV.

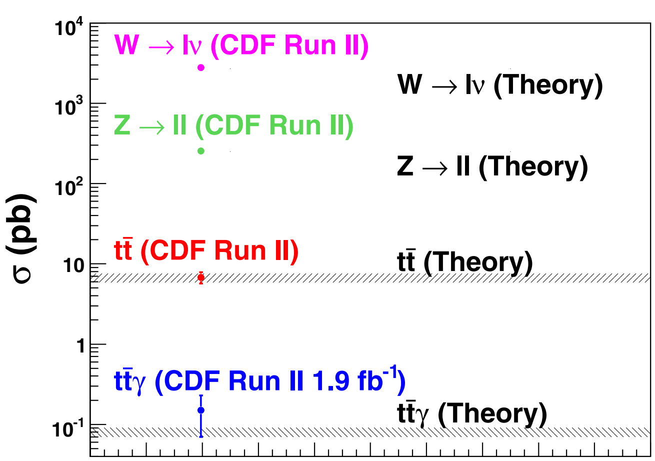

FIG. 6 (color online). Estimate of $\sigma_{t\bar{t}\gamma}$ compared with SM expectations and other SM cross sections $\sigma_{W^\pm\to\ell^\pm\nu}$, $\sigma_{Z\to\ell^+\ell^-}$ and $\sigma_{t\bar{t}}$ [32].

of this search we have also performed a search for the SM process $p\bar{p} \to t\bar{t}\gamma$, which is predicted to be the dominant process that produces this signature with at least 3 jets and large total transverse energy H_T. Here too we find good agreement with the SM expectations. Although not statistically significant, the number of observed $t\bar{t}\gamma$ events is larger than the SM prediction not including $t\bar{t}\gamma$ production. Assuming the difference between the observed number and the predicted non-top-quark SM total is due to top-quark production, we estimate the $t\bar{t}\gamma$ cross section to be 0.15 ± 0.08 pb.

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[5] Transverse momentum and energy are defined as $p_T = p\sin\theta$ and $E_T = E\sin\theta$, respectively. Missing E_T ($\not{E}_T$) is defined by $\not{\vec{E}}_T = -\sum_i E_T^i \hat{n}_i$, where i is the calorimeter tower number for $|\eta| < 3.6$ (see Ref. [6]), and $\hat{n}_i$ is a unit vector perpendicular to the beam axis and pointing at the ith tower. We correct $\not{\vec{E}}_T$ for jets and muons. We define the magnitude $\not{E}_T = |\not{\vec{E}}_T|$. We use the convention that momentum refers to pc and mass to mc^2.

[6] The CDF coordinate system of r, φ, and z is cylindrical, with the z-axis along the proton beam. The pseudorapidity is $\eta = -\ln(\tan(\theta/2))$.

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[22] 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 20 GeV.

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

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