Search for New Physics in Lepton + Photon + Missing Transverse Energy + b-jets Events and $t\bar{t}\gamma$ Cross-Section measurement

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We present the results of a search for anomalous production of events containing a charged lepton (ℓ, either e or μ), a photon (γ), missing transverse energy ($\not{E}_T$) and b jets, all with high transverse momentum. We also present the results of a search for $t\bar{t}\gamma$ semi-leptonic events. The analyses have been performed using 929 pb-1 of integrated luminosity from p$\bar{\text{p}}$ collisions at $\sqrt{s} = 1.96$ TeV collected using CDF II detector at the Fermilab Tevatron. We find 15 $\ell\gamma\not{E}_T b$ events versus an expectation of 14.3 ± 1.6 events. We observe 7 $t\bar{t}\gamma$ candidate events versus an expectation of 3.6 ± 0.8.

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An important test of the standard model (SM) of particle physics [1] is to measure and understand the properties of the highest momentum-transfer particle collisions, and therefore to study interactions at the shortest distances. The major predictions of the SM for these collisions are the rates for the events of a given type, and their associated kinematic distributions.

However, the predicted high energy behavior of the SM, becomes unphysical at an interaction energy on the order of several TeV. Therefore, new physical phenomena are required to ameliorate this high-energy behavior. These unknown phenomena may involve new fundamental forces, new elementary particles, and/or a modification of space-time geometry. The new phenomena are likely to manifest themselves as an anomalous production rate of a combination of the known fundamental particles.

The unknown nature of possible new phenomena in the energy range accessible at the Tevatron is the motivation for a "signature-based" search strategy that does not focus on a single model or class of models of new physics, but presents a wide net for new phenomena.

In this note we report the results of a search for anomalous production of $\ell\gamma\not{E}_T b$ events, and the results of a search for $t\bar{t}\gamma$ events in a semi-leptonic channel using 929 pb-1 of integrated luminosity from p$\bar{\text{p}}$ collisions at $\sqrt{s} = 1.96$ TeV collected using CDF II detector [2]. The events for the searches include production of two gauge bosons, W and γ, and two third generation quarks, top and bottom.

We realized that a search for $t\bar{t}\gamma$ is a natural extension of the signature-based search we had been doing, in that $t\bar{t}\gamma$ is characterized by the signature of a high-P_T lepton, photon, b-tagged jet, and $\not{E}_T$. When one in addition requires large H_T and 3-or-more jets radiative top events dominate the SM predictions. The 'mother' analysis of the lepton+photon+X signature is described in Ref. [3].

The CDF II detector is a cylindrically symmetric spectrometer designed to study p$\bar{\text{p}}$ collisions at the Fermilab Tevatron based on the same solenoidal magnet and central calorimeters as the CDF I detector [4] from which it was upgraded. The tracking systems used to measure the momenta of charged particles have been replaced with a central outer tracker (COT) with smaller drift cells [5], and an enhanced system of silicon strip detectors [6]. The calorimeters in the regions [7] with pseudorapidity $|\eta| > 1$ have been replaced with a more compact scintillator-based design, retaining the projective geometry [8]. The coverage in φ of the CMP and CMX muon systems [9] has been extended; the CMU system is unchanged [2].

A 3-level trigger [2] system selects events with a high transverse momentum (P_T) [10] lepton in the central region, $|\eta| \lesssim 1.0$. The trigger system selects 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 $\text{E}_\text{T}^\gamma > 10$ GeV and a central e or μ with $\text{E}_\text{T}^\ell > 20$ 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 II $\ell\gamma + X$ search [3].

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$\bar{\text{p}}$ collision. An electron candidate passing the "tight" selection must have: a) a high-quality track with $\text{P}_\text{T} > 0.5$ E_T, unless $\text{E}_\text{T} > 100$ 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 two calorimeter towers containing the electron shower consistent with that expected; and d) minimal leakage into the hadron calorimeter [11].

Photon candidates are required to have no track with $\text{P}_\text{T} > 1$ GeV, and at most one track with $\text{P}_\text{T} < 1$ GeV, pointing at the calorimeter cluster; good profiles in both transverse dimensions at shower maximum; and minimal leakage into the hadron calorimeter [11].

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

CDF Run II Preliminary, $929pb^{-1}$			
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	0.98 ± 0.11	0.72 ± 0.081	1.70 ± 0.19
$t\bar{t}\gamma$ dileptonic	0.60 ± 0.065	0.48 ± 0.052	1.08 ± 0.11
$W^{\pm}c\gamma$	0.29 ± 0.060	0.29 ± 0.058	0.58 ± 0.094
$W^{\pm}cc\gamma$	0.047 ± 0.020	0.099 ± 0.028	0.15 ± 0.035
$W^{\pm}bb\gamma$	0.29 ± 0.048	0.20 ± 0.037	0.49 ± 0.069
$Z(\tau\tau)\gamma$	0.12 ± 0.07	0.05 ± 0.05	0.17 ± 0.09
WZ	0.029 ± 0.014	0.0 ± 0.0075	0.029 ± 0.016
$\tau \rightarrow \gamma$ fake	0.06 ± 0.02	0.05 ± 0.02	0.11 ± 0.03
$ee\not\!\!E_T b$, $e\rightarrow\gamma$	1.05 ± 0.21	–	1.05 ± 0.21
$\mu e\not\!\!E_T b$, $e\rightarrow\gamma$	–	0.24 ± 0.08	0.24 ± 0.08
Jet faking γ	0.73 ± 0.34	0.46 ± 0.20	1.19 ± 0.54
MisTags	2.85 ± 0.35	1.89 ± 0.26	4.74 ± 0.51
QCD	2.85 ± 1.32	0.0 ± 0.50	2.85 ± 1.41
Predicted	$9.8 \pm 1.4(tot)$	$4.5 \pm 0.6(tot)$	$14.3 \pm 1.6(tot)$
Observed	7	8	15

TABLE I: Summary for $\ell\gamma\not\!\!E_T b$ signature-based search. Backgrounds from WW, ZZ, single top + γ are found to be negligible

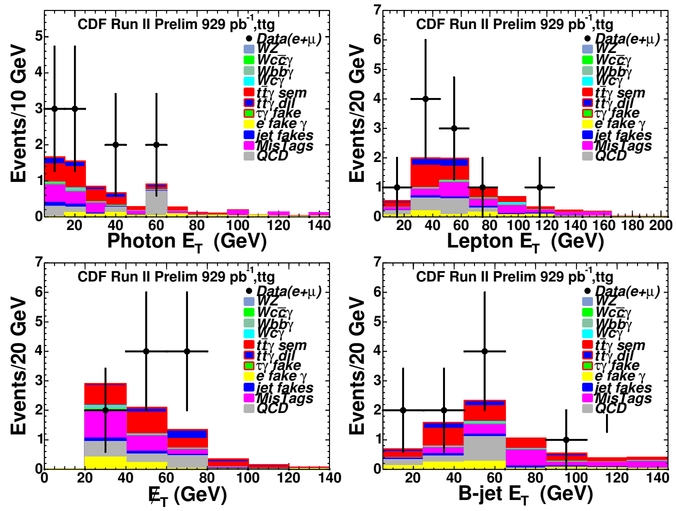

FIG. 1: The distributions for events in the $\ell\gamma\not\!\!E_T b$ sample (points) in a) the E_T of the photon; b) the E_T of the lepton; c) the missing transverse energy, $\not\!\!E_T$; and d) the E_T of the b jet. The histograms show the expected SM contributions, including estimated backgrounds from misidentified photons and leptons.

$\eta - \varphi$ space [7] 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 non-uniform calorimeter response [12] for jets with uncorrected $E_T > 15\ GeV$ and $\eta < 2.0$, and for muons with $P_T > 20\ GeV$.

The first search we perform is in the $\ell\gamma\not\!\!E_T b + X$ subsample, defined by requiring that an event contains $\not\!\!E_T > 20\ GeV$, a photon with $E_T^{\gamma} > 10\ GeV$, a "tight" lepton with $E_T^{\ell} > 20\ GeV$ and a b-tagged jet with $E_T^{jet} > 15\ GeV$. Figure 1 shows the observed distributions in a) the E_T of the photon; b) the E_T of the lepton; c) $\not\!\!E_T$; and d) the E_T of the b-tagged jet.

Figure 2 shows the observed distributions in the total transverse energy H_T, the sum of the transverse energies of the lepton, photon, jets and $\not\!\!E_T$, for the $\ell\gamma\not\!\!E_T b$ events.

Figure 3 shows the distribution for the total number of jets in $\ell\gamma\not\!\!E_T b$ events with $H_T > 200\ GeV$. For the search for $t\bar{t}\gamma$ events we require $H_T > 200\ GeV$ [13] along with $N_{jets} > 2$.

We also check $\ell\gamma\not\!\!E_T b$ events for presence of additional objects, for instance, another e, μ, γ or jets in addition to the "tight" lepton, the γ, b-tagged jet and $\not\!\!E_T$. 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 $E_T > 20\ GeV$ 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 [14].

However, we do not find $\ell\gamma\not\!\!E_T b$ events with additional leptons or photons.

We have estimated the background due to events with jets misidentified as $\ell\gamma\not\!\!E_T b$ signature by studying the total P_T of tracks in a cone in $\eta - \varphi$ space of radius R=0.4 around the lepton track (track isolation). We compared distribution of track isolation in our signal sample to that of the $Z^0 \rightarrow e^+e^-$ and $Z^0 \rightarrow \mu^+\mu^-$ samples (for the electron and the muon channels, respectively) and to that of the QCD background sample (generic jet sample, dominated by light-flavor jets).

The number of "jet faking photon" events expected in the $\ell\gamma\not\!\!E_T b$ signature is determined by measuring the jet E_T spectrum in $\ell j\not\!\!E_T b$ samples, and then multiplying by the probability of a jet being misidentified as a photon, which is measured in data samples triggered on jets [15].

The number of "electron faking photon" events expected in the $\ell\gamma\not{E}_T b$ signature is determined by measuring the photon E_T spectrum in $\ell e\not{E}_T b$ samples, and then multiplying by the probability of an electron being misidentified as a photon, which is measured in $Z^0 \rightarrow e^+e^-$ events in which one of the electrons radiates a high-E_T photon.

To estimate the size of the mistag background, each jet in the $\ell\gamma\not{E}_T$+pretagged jet sample is weighted by its mistag rate. The mistag rate per jet is measured using a large inclusive-jet data sample.

Tau faking photon background is estimated from $t\bar{t}$ PYTHIA] [16] sample by selecting $\tau \rightarrow$ *hadrons* $\rightarrow \gamma$ events using MC information and then applying same analysis cuts as for data.

The production of semileptonic $t\bar{t}$+photon with one of the W bosons decaying leptonically (e, μ and τ channels), and another hadronically is estimated from the MADGRAPH [17] MC. The production of dileptonic $t\bar{t}$+photon with both W bosons decaying leptonically (e, μ and τ channels) is also estimated from the MADGRAPH MC. The SM background from a production of a W boson and a photon, accompanied by QCD production of heavy flavor quarks in the processes $Wb\bar{b}$+photon, $Wc\bar{c}$+photon, and Wc+photon, is estimated from MADGRAPH MC. Backgrounds from WW, ZZ, single top + photon are estimated to be negligible.

The predicted and observed totals for the $\ell\gamma\not{E}_T b$ are shown in Table I. The predicted and observed totals for the $t\bar{t}\gamma$ are shown in Table II.

In conclusion, we have performed the search for inclusive lepton + photon + $\not{E}_T$ + b-jets production, as well as the search for $t\bar{t}\gamma$ semi-leptonic events. We find that the numbers of events agree with SM predictions. We find 15 $\ell\gamma\not{E}_T b$ events versus an expectation of 14.3 ± 1.6 events. We observe 7 $t\bar{t}\gamma$ candidate events versus an expectation of 3.6 ± 0.8.

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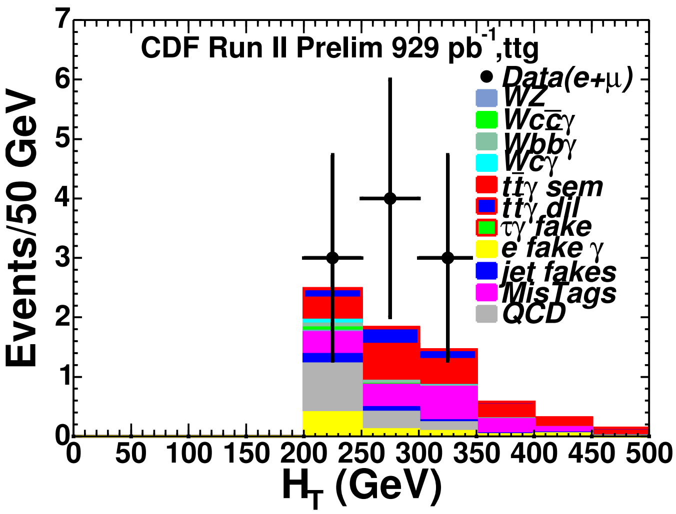

FIG. 2: The distributions for the total transverse energy H_T, the sum of the transverse energies of the lepton, photon, jets and $\not{E}_T$, for the $\ell\gamma\not{E}_T b$ events. The histograms show the expected SM contributions.

CDF Run II Preliminary, $929pb^{-1}$			
	$t\bar{t}\gamma$ Candidate Events		
SM Source	e	μ	$e+\mu$
$t\bar{t}\gamma(semileptonic)$	0.89 ± 0.097	0.65 ± 0.073	1.54 ± 0.17
$t\bar{t}\gamma(dileptonic)$	0.18 ± 0.021	0.14 ± 0.017	0.32 ± 0.035
$W^{\pm}c\gamma$	0.0 ± 0.011	0.0 ± 0.011	0 ± 0.016
$W^{\pm}cc\gamma$	0.0 ± 0.0082	0.0078 ± 0.0078	0.0078 ± 0.011
$W^{\pm}bb\gamma$	0.020 ± 0.010	0.0049 ± 0.0049	0.025 ± 0.011
WZ	0.0 ± 0.0075	0.0 ± 0.0075	0 ± 0.011
$\tau \rightarrow \gamma$ fake	0.04 ± 0.01	0.01 ± 0.01	0.05 ± 0.02
$ee\not{E}_T b$, $e \rightarrow \gamma$	0.22 ± 0.08	–	0.22 ± 0.08
$\mu e\not{E}_T b$, $e \rightarrow \gamma$	–	0.19 ± 0.06	0.19 ± 0.06
Jet faking γ	0.08 ± 0.050	0.03 ± 0.020	0.11 ± 0.07
MisTags	0.22 ± 0.12	0.31 ± 0.18	0.53 ± 0.22
QCD	0.72 ± 0.61	0.0 ± 0.50	0.72 ± 0.79
Predicted	$2.3 \pm 0.6(tot)$	$1.3 \pm 0.5(tot)$	$3.6 \pm 0.8(tot)$
Observed	4	3	7

TABLE II: Summary for $t\bar{t}\gamma$ ($\ell\gamma\not{E}_T b + H_T > 200GeV + N_{jets} > 2$). Backgrounds from WW, ZZ, single top + γ are found to be negligible

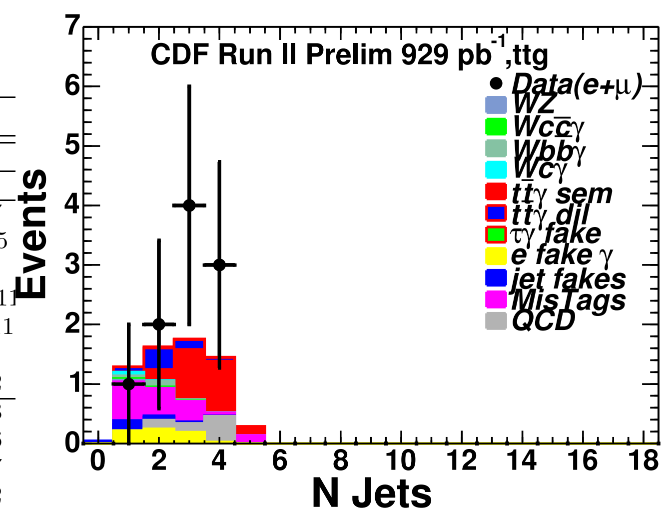

FIG. 3: The distribution for the total number of jets in $\ell\gamma\not{E}_T b$ events with $H_T > 200$ GeV, where H_T is the total transverse energy , the sum of the transverse energies of the lepton, photon, jets and $\not{E}_T$. For the search for $t\bar{t}\gamma$ events in addition to $H_T > 200$ GeV we also require $N_{jets} > 2$. The histograms show the expected SM contributions.

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[7] 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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[9] The CMU system consists of gas proportional chambers in the region $|\eta| < 0.6$; the CMP system consists of chambers after an additional meter of steel, also for $|\eta| < 0.6$. The CMX chambers cover $0.6 < |\eta| < 1.0$.

[10] Transverse momentum and energy are defined as $\mathrm{P_T} = p\sin\theta$ and $\mathrm{E_T} = E\sin\theta$, respectively. Missing $\mathrm{E_T}$ ($\vec{\not{E}}_T$) 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. [7]), 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 $\not{E}_\mathrm{T} = |\vec{\not{E}}_T|$. We use the convention that "momentum" refers to pc and "mass" to mc^2.

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

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