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A Signature-Based Search for Anomalous $\ell\gamma\not{E}_T$ + b-jet Production and SM $t\bar{t}+\gamma$ Production in 4.8 fb^{-1} with the CDF-II detector

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Abstract

We present a search for anomalous production of the signature ℓ+γ+b-quark+$\not{E}_T$ produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV using 4.8 fb^{-1} of data taken with the CDF detector in Run II at the Tevatron. In addition to this signature-based search, we present a search for top pair production with an additional radiated photon, $t\bar{t}+\gamma$. We find 61.00 $\ell\gamma\not{E}_T b$ events versus an expectation of $60.78^{+4.54}_{-xxx}$ events. Additionally requiring the events to contain at least 3 jets and to have a total transverse energy of 200 GeV, we observe 26.00 $t\bar{t}\gamma$ candidate events versus an expectation from non-top standard model (SM) sources of $14.88^{+2.45}_{-xxx}$. Assuming the difference between the observed number and the predicted non-top SM total is due to top production, we measure the $t\bar{t}\gamma$ cross-section to be .076 $\pm$ .039 pb. We also measure a ratio of the $t\bar{t}\gamma$ cross-section to the $t\bar{t}$ cross-section to be $xxx \pm xxx$.

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1 Introduction

In this note we present a search for anomalous production of events with a high-P_T lepton (electron e or muon μ), photon (γ), jet tagged as containing b-meson (b-jet), and missing transverse energy ($\not\!\!E_T$) ($\ell\gamma\not\!\!E_T b$ events), using 4.8 fb^{-1} of integrated luminosity from $\bar{p}p$ collisions at $\sqrt{s} = 1.96$ TeV collected using the CDF II detector [?]. This search is an improvement of a previous analysis, described in detail in Ref. [3].

A search for the production of top pairs with an additional photon, $t\bar{t}\gamma$, is a natural extension of this signature-based search, as the $t\bar{t}\gamma$ is characterized by the same $\ell\gamma\not\!\!E_T b$ signature. Additional cuts are then applied so that radiative top-pair events dominate the SM predictions: we require large H_T (the sum of the transverse energies of the lepton, photon, jets and $\not\!\!E_T$) and 3-or-more jets.

The $\ell\gamma\not\!\!E_T b$ signature is possible [4] in different models beyond the SM, such as gauge-mediated Supersymmetry (SUSY) models [5]. The signature has known SM backgrounds, and could be produced in decays of heavy particles. This type of signature contains fundamental particles, such as two third-generation quarks, t-quark and b-quark, and two gauge bosons, W ($W \rightarrow \ell\nu$) and γ. This search is related to the $\ell\gamma + X$ search [6], but with b-tag requirement in addition to lower photon E_T, lepton P_T and $\not\!\!E_T$ requirements.

Although the top quark has been discovered more than 10 years ago, many of its properties are still poorly known. For example, the coupling of the the top quark to electroweak gauge boson has not yet directly measured. The $t\bar{t}\gamma$ production could be used as a tool to measure the $tt\gamma$ coupling [4]. The $t\bar{t}\gamma$ will also serve as a control sample for $t\bar{t}$+Higgs production at the LHC and a probe of the charge of the top quark [7].

2 Datasets

The data presented in the analysis represent 4.8fb^{-1} for which the silicon detector and all three central muon systems CMP, CMU and CMX were operational. Previous results for these analyses with $929pb^{-1}$ and 1.9fb^{-1} of data are described in [8] and [9] respectively.

The $\mu\gamma\not\!\!E_T b$ sample is taken from the inclusive high-P_T muon samples: *bhmu0d*, *bhmu0h*, *bhmu0i* , *bhmu0j*, *bhmu0k*, and *bhmu0m*. The $e\gamma\not\!\!E_T b$ sample is obtained from the inclusive high-P_T electron samples: *bhel0d*, *bhel0h*, *bhel0i* and *bhel0j*, *bhel0k*, and *bhel0m*.

Each of these samples was ntupled using the TTGNtupler package (Appendix A.3). In both previous analyses the ntupling was done using the UC flat ntuple details of which can be found in [10, 11].

To select events for the $\ell\gamma\not\!\!E_T b$ category we require an event to have a tight lepton, a photon, $\not\!\!E_T > 20GeV$ and a b-jet with $E_T > 15$. The selection criteria are described in the Section B. The electron criteria are listed in Tables B.2 and B.3; the muon criteria in Table B.1; the photon criteria are listed in Table B.4; the b-jet - in Section B.4.

To select events for the $t\bar{t}\gamma$ category we apply the same cuts as for the $\ell\gamma\not\!\!E_T b$ category with two additional requirement, $H_T > 200GeV$ and number of jets > 2.

2.1 Selecting Candidate Events from Data

To reduce processing time, we took a few steps too select events. At the first step (STNtuple $\rightarrow$ TTGNtuple) we required an event to contain at least one loose electron (Table B.2, we required $E_T^e > 12$ GeV cut), or at least one loose muon (Table B.1, we required $P_T^\mu > 12$ GeV cut), or an anti-electron (Table **anti-electron selection criteria**). We performed this step on CDF CAFs, and output TTGNtuples were saved on the University of Chicago (UC) disk space (Appendix A.3).

At the second step we have selected events needed for signal and background studies, and also for cross-checks of W, Z, $\ell\gamma\not{E}_T$ and $\ell\ell$ event yields for different data-taking periods. We performed this step on the University of Chicago batch system and output TTGNtuples were saved on the UC disk space (Appendix A.3).

In Table A.5 we list the raw number of events in the datasets as well as the number of events that we select from these datasets. We also list run ranges for the datasetes.

3 New MadGraph Samples

3.1 Introduction: The Matrix Element Generators

The dominant source of $\ell\gamma\not{E}_T b$ and $t\bar{t}\gamma$ events at the Tevatron is $t\bar{t}\gamma$ production followed by $t \to Wb$, in which one W boson decays leptonically and the other one - hadronically.

The number of $\ell\gamma\not{E}_T b$ and $t\bar{t}\gamma$ events from $t\bar{t}\gamma$ production is estimated using leading-order (LO) Monte Carlo event generator program MadGraph [12] (kinematic cuts are listed in Table 3.1).

This program output 4-vectors and helicities of particles emanating from a diboson production event in an ASCII format. In addition the information on how the particles are produced ("mother" and "daughter") is recorded, including the energy scale and other parameters used for the matrix element calculation.

These files are then fed into the LesHouchesModule [13], which runs Pythia to add parton fragmentation and final-state radiation and initial-state radiation (both QED and QCD) , and then writes out the events in CDF HEPG format. These files are then used as input to the CDF detector simulation program. This program outputs simulated data in a format identical to that of an actual CDF Run II event. Simulated $\ell\gamma\not{E}_T b$ event rates can then be estimated in a manner identical to that of CDF data.

We performed additional check of MadGraph $t\bar{t}$ MC. We generated $t\bar{t}$ MC with MadGraph and compared cross-sections of the processes with standard CDF Top group MC.

3.2 $t\bar{t}\gamma$ MC Samples

The information about new MadGraph samples including all cuts / settings etc is listed in this section. The information (**unchanged - why would we even keep it in the appendix?.. MERGE IT with this section!!**) about datasets used for 1.9 fb^{-1} analysis is in Appendix **??**.

To generate $t\bar{t}\gamma$ and $\ell\gamma\not{E}_T b$ MC we employed MadGraph and requested the dileptonic contribution be split into three pieces shown below:

The processes above show the t quark or tbar quark decaying to a b quark, charged lepton, and corresponding neutrino. The top (anti top) quark decay to a W boson and b (anti-b) quark. The W boson then decays to a charged lepton. In the first process, either the initial quarks of the proton, the top quark, or the anti-top quark radiate a photon. In the other two process, a decay product of the top, or anti-top, quark radiates off a photon.

The process for semileptonic decay of ttbar plus a photon is broken down into six sub processes for ease of running on the MadGraph website as well as simulating locally. There have been 15 runs generated, and the following table shows the number of events contained per run.

As a comparison I am showing the results from the 1.9 fb^{-1} note for $t\bar{t}\gamma$ cross sections which can be seen in Table 3.1.

We also simulated three W decays to heavy flavor quarks.

DataSet Name	Events	Crossection (pb)
Mad_$t\bar{t}\gamma$ semileptonic (e and μ)	43724	0.0726349
Mad_$t\bar{t}\gamma$ dileptonic (e and μ)	33801	0.0216773

Table 3.1: The $t\bar{t}\gamma$ MadGraph datasets.

DataSet Sample	Events per Run	Cross Section (pb)	Cross Section Uncertainty
(t$\rightarrow \bar{d}ub$)($\bar{t} \rightarrow \bar{b}l^-\bar{\nu}$)a	17,304	0.009737	0.000024
(t$\rightarrow \bar{s}cb$)($\bar{t} \rightarrow \bar{b}l^-\bar{\nu}$)a	9,134	0.009730	0.000016
(t$\rightarrow \bar{d}uba$)($\bar{t} \rightarrow \bar{b}l^-\bar{\nu}$)	1,236	0.003954	0.000040
(t$\rightarrow \bar{s}cba$)($\bar{t} \rightarrow \bar{b}l^-\bar{\nu}$)	1,248	0.003953	0.000030
(t$\rightarrow \bar{d}ub$)($\bar{t} \rightarrow \bar{b}l^-\bar{\nu}$a)	1,284	0.006206	0.000237
(t$\rightarrow \bar{s}cb$)($\bar{t} \rightarrow \bar{b}l^-\bar{\nu}a$)	1,284	0.006206	0.000237
ttg_Semileptonic	xxx	0.039720	0.000360
(t$\rightarrow bl+\nu$)($\bar{t} \rightarrow \bar{b}l^-\bar{\nu}$)a	12,623	0.010349	0.000019
(t$\rightarrow bl+\nu$)($\bar{t} \rightarrow \bar{b}l^-\bar{\nu}a$)	1,365	0.006685	0.000430
(t$\rightarrow bl+\nu$a)($\bar{t} \rightarrow \bar{b}l^-\bar{\nu}$)	1,126	0.006444	0.001224
ttg_Dileptonic	xxx	0.023478	0.001297

Table 3.2: The $t\bar{t}\gamma$ Semileptonic and Dileptonic Decay MadGraph datasets. In each of these decays the lepton may be any of the three flavors.

DataSet Sample	Events per Run	Cross Section (pb)	Cross Section Uncertainty
W$\rightarrow l^+\bar{\nu}+\bar{b}b\gamma$ (e, μ, τ)	2,677	0.054738	0.000113
W$\rightarrow l^+\bar{\nu}+\bar{c}c\gamma$ (e, μ, τ)	17,244	0.10097	0.000410
W$\rightarrow l^+\bar{\nu}+c\gamma$ (e, μ, τ)	17,329	0.4386	0.0009

Table 3.3: The W plus heavy flavor decay MadGraph datasets. In each of these decays the lepton can take on any of three flavors of lepton.

The full list of our requirements on the event kinematics is shown below:

```
#*********************************************************************
# Minimum pt's                                                       *
#*********************************************************************
  6  = ptj ! minimum pt for the jets
  6  = ptb ! minimum pt for the b
  6  = pta ! minimum pt for the photons
  6  = ptl ! minimum pt for the charged leptons
#*********************************************************************
# Maximum rapidity                                                   *
#*********************************************************************
 4.0  = etaj ! max rap for the jets
 4.0  = etab ! max rap for the b
 2.0  = etaa ! max rap for the photons
```

```
 4.0  = etal ! max rap for the charged leptons
#*********************************************************************
# Minimum DeltaR distance                                            *
#*********************************************************************
 0.4 = drjj ! distance between jets
 0.4   = drbb ! distance between b's
 0.4 = drll ! distance between leptons
 0.4 = draa ! distance between gammas
 0.4   = drbj ! distance between b and jet
 0.4 = draj ! distance between gamma and jet
 0.4 = drjl ! distance between jet and lepton
 0.4   = drab ! distance between gamma and b
 0.4   = drbl ! distance between b and lepton
 0.4 = dral ! distance between gamma and lepton
#*********************************************************************
# Minimum invariant mass for pairs                                   *
#*********************************************************************
 0  = mmjj ! min invariant mass of a jet pair
 10  = mmbb ! min invariant mass of a b pair
 0  = mmaa ! min invariant mass of gamma gamma pair
 10  = mmll ! min invariant mass of l+l- (same flavour) lepton pair
#*********************************************************************
```

3.3 The other SM Diboson Processes as Sources of $\ell\gamma \not{E}_T b$ and $t\bar{t}\gamma$ Events

We consider WZ, W$c\bar{c}\gamma$, W$\bar{b}\gamma$ and W$c\gamma$ as the other sources for $\ell\gamma \not{E}_T b$ and $t\bar{t}\gamma$ events.

We use $t\bar{t}$ sample (ttopel) for estimating $\tau \rightarrow hadron \rightarrow \gamma$ fake rate.

The generator-level monte carlo events were run through Pythia. They were then run through CdfSim and 5.3.3 Production, and then ntupled [10]; a tabulation of the datasets is given in Ref. [10].

The description of these MC Sample:

```
sample              x-sec,pb     events
---------------------------------------
WZ                  3.65         409648
Wbbgamma            0.03737      12279
Wcgamma             0.29904      48261
Wccgamma            0.069102     14152
ttbar (ttopel)      6.1          1146088

---------------------------------------
```

4 Backgrounds: Fakes

In addition to the expectations from real SM processes that produce real $\ell\gamma\not\!\!E_{\mathrm{T}}b$ and $t\bar{t}\gamma$ events described in Section **??**, there are backgrounds due to misidentified leptons, photons and b-tags, and also incorrectly calculated $\not\!\!E_{\mathrm{T}}$. We generically call these misidentifications 'fakes'.

4.1 Misidentified Photons

We consider three sources of fake photons: QCD jets in which a neutral hadron or photon from hadron decay mimics a direct photon, electron bremsstrahlung, in which an energetic photon is radiated off of an electron which is then much lower energy and curls away from the photon, and also photons from tau decays $\tau \to hadron + \gamma$.

4.1.1 Jets Faking Photon

High $\mathrm{P_T}$ photons are 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 $\ell\gamma\not\!\!E_{\mathrm{T}}b$ and $t\bar{t}\gamma$ samples are determined by measuring energy in the calorimeter nearby the photon candidate.

For each of the four samples, $e\gamma\not\!\!E_{\mathrm{T}}b$, $\mu\gamma\not\!\!E_{\mathrm{T}}b$, $t\bar{t}\gamma$ (e channel), and $t\bar{t}\gamma$ (μ channel), Figure 4.1 shows the distribution in the total (electromagnetic plus hadronic) calorimeter energy, $\mathrm{E_T^{\mathit{Iso}}}$, in a cone of radius $R = 0.4$ in η-ϕ space around the photon candidate. This distribution is then fitted to the shape measured for electrons from $\mathrm{Z}^0 \to e^+e^-$ decays plus a linear background.

To verify the linear behaviour of the background we create fake photon sample. To create the sample we require $\chi^2_{CES} > 20$ to reject real photons; we also omit calorimeter and track isolation requirements. The distribution in the total calorimeter energy, $\mathrm{E_T^{\mathit{Iso}}}$, in a cone in η-ϕ space around the fake photon candidate, is shown in Figure 4.2.

The predicted number of events with jets misidentified as photons is 13.80 ± 1.70 for the $\ell\gamma\not\!\!E_{\mathrm{T}}b$ signature and 11.10 ± 1.76 for the $t\bar{t}\gamma$ events.

4.1.2 Electron Faking Photon

To determine the rate at which an electron fakes an isolated photon ($e \to \gamma$) in the central EM Calorimeter (CEM) we use Method-B described in [14]. The method provides a probability for an electron passing the standard tight electron cuts to fake a photon by extracting the ratio of the number of $Z^0 \to e\gamma$ events relative to $Z^0 \to ee$ events. That's the same method we used for 1.9 fb^{-1} analysis [9]. This gives a probability for an electron to fake a photon. We select events with a b-jet, substantial $\not\!\!E_{\mathrm{T}}$, and a tight lepton, and further require a selection of electrons capable of faking photons. These list of electrons capable of faking photons includes all tight electrons with $\mathrm{P_T}$ greater than 12 GeV, as well as all loose electrons.

We then weight each event by the probability of the electron faking a photon divided by the number of possible combinations of electrons capable of faking photons in the event.

The predicted number of events with electrons misidentified as photons is 4.94 ± 0.37 for the $\ell\gamma\not\!\!E_{\mathrm{T}}b$ signature and 1.24 ± 0.17 for the $t\bar{t}\gamma$ events.

4.1.3 $\tau \to \gamma$ Fake Rate

In addition to estimating number of $\ell\gamma\not\!\!E_{\mathrm{T}}b$ and $t\bar{t}\gamma$ events with jet faking photon ($j \to \gamma$), we also estimate number of events with tau faking photon ($\tau \to \gamma$).

Fake rate $j \to \gamma$ is of order of 10^{-4} or smaller (Ref. [15]). Fake rate for tau's is expected to be $\approx 10^{-2}$ which is two orders of magnitude larger. Due to the way jets fragment it is much harder for a jet to produce a single isolated (high p_T) π^0 compared to a tau.

We evaluate $\tau \to \gamma$ fake rate from the $t\bar{t}$ Monte Carlo sample (ttopel sample). On the first step we select events on HEPG level with of the W's going to $\tau\nu$, $\tau \to hadron + \gamma$. Then we apply our analysis cuts to the stripped sample.

In total for $\ell\gamma \not\!\!E_T b$ category we observe 0.55± 0.23 $\tau \to \gamma$ events. For the $t\bar{t}\gamma$ category we observe 0.23 ± 0.07 $\tau \to \gamma$ events.

4.2 Misreconstructed b-jets

According to the procedure described in Ref. [16], in an event loop, first we cache all of the jets so a mistag matrix knows the event SumEt. We use raw (uncorrected), jet Et for the mistag matrix. We cache all jets with $E_T > 10$ GeV, $|\eta| < 2.4$. The mistag matrix identifies the parameters α and β. The former accounts for the amount of heavy flavor contribution in jets not identified as b-tagged, and the latter accounts for the amount of heavy jets in the sample compared to lighter flavor jets. **CITE CDF 8626** The rate of negative mistags, R^-_{mistag}, α, and β are defined below.

$$R^-_{mistag} = \frac{N^-_{light} + N^-_{heavy}}{N^{pre}_{light} + N^{pre}_{heavy}}$$

$$\alpha = \frac{N^+_{light}}{N^-_{light} + N^-_{heavy}}$$

$$\beta = \frac{N^{pre}_{light} + N^{pre}_{heavy}}{N^{pre}_{light}}$$

$$\alpha\beta R^-_{mistag} = \frac{N^+_{light}}{N^{pre}_{light}}$$

The positive and negative signs show whether a jet was tagged as a b-jet (+) or was not tagged as a b-jet (-). The pre superscript, dictates the amount of objects in the sample before the tagging value was applied. The subscript heavy denotes either b or c flavor jets. The parameters α, β, and R^-_{mistag} were determined using Monte Carlo and jet matching. The results are the compared to data for inclusive jets samples, and corrected with an overall scale factor.

After the mistag matrix is calculated we loop over the identified jets again and get the predicted tag rates and errors.

For a mistag file we are using to :
BTagObjects/mistag_4100invpb/LooseSECVTXparam_4100invpb.root and tag type "loose".

Once we have the rate at which a jet likely to be mistagged we define a sample of events that contain a tight lepton, a tight photon, and a taggable jet, and $\not\!\!E_T$ that passes our cuts. We then find the expected number of mistagged events to be our sample weighted by its respective mistag weight.

4.3 QCD (Jets Faking Lepton and $\not\!\!E_T$)

To estimate the contribution of our signal due to QCD processes faking leptons and $\not\!\!E_T$ we follow the lead of B. Cooper and A. Messina in CDF note 7760. We look for electron candidates that fail at least two of the following cuts:

- list of cuts

We require a b-tagged jet, a photon, an anti-electron and then plot the $\not{E}_T$ of the event. We compare this to MC processes, and data, requiring a true lepton, a b-tagged jet, and a photon. The region below 20 GeV of $\not{E}_T$ is fit to the data using MC and the anti-electron sample. The MC is scaled by cross sections and luminosity, and the anti-electron sample is scaled to minimize the chi squared fit in the 0-20 GeV $\not{E}_T$ region. The anti-electron $\not{E}_T$ distribution is then integrated from 20-infinity. The distributions used to find this background are shown in Figure 4.5. The uncertainty on these measurements come from the statistical uncertainty on the number of points, as well as the systematic uncertainty due to the chi sqaured fit.

4.4 Double Counting of Fake Events

We describe an example procedure how we estimate and subtract double counting in our background estimates.

1. For instance, let's consider $e \to \gamma$ background. It is obtained by selecting $e\ell b\not{E}_T + N_{jets}$ events, and each event is then multiplied by $f.r.(e \to \gamma)$. Therefore, we get expected number of events:

   $N1 = (e \to \gamma)\ell b\not{E}_T + N_{jets}$

2. Now let's estimate a number of events with fake b, $j \to b$. We start from $\gamma\ell j\not{E}_T + N_{jets}$, and each event is then multiplied by $f.r.(j \to b)$. Therefore, we get expected number of events

   $N2 = \gamma\ell(j \to b)\not{E}_T + N_{jets}$

3. obviously, some of the events with fake photon $(e \to \gamma)$ also have fake b $(j \to b)$, so if we just take a total N1+N2, then we will overestimate our backgrounds. Therefore, we need to subtract the overlap between the two, which is

   $N1N2 = (e \to \gamma)\ell(j \to b)\not{E}_T + N_{jets}$

   and therefore

   $N = N1 + N2 - N1N2$

4. To get this, we should apply step **2** to the events from which you obtain $(e \to \gamma)$ background. Therefore, we take events with $e\ell j\not{E}_T + N_{jets}$ and multiply each of them by $f.r.(e \to \gamma) \times f.r.(j \to b)$

5. If you apply "antielectrons" procedure, then you normally apply it to a sample of l+X (where "X = N_{jets}" is the case described in the antielectrons note). You can do the same with l+X, where X = $\gamma b + N_{jets}$, and to avoid double counting with $e \to \gamma$ you would apply the procedure to $\ell(e \to \gamma)b + N_{jets}$ i.e. you would start from $\ell eb + N_{jets}$ events, apply $f.r.(e \to \gamma)$ and at the same time repeat "antielectrons" procedure.

4.5 Double Counting of Jets Faking Photons, and Electrons Faking Photons

To measure the amount of jets faking photons and electrons faking photons requires substantial $\not{E}_T$, a b-tagged jet, and a tight lepton. The overlap comes from events which also have a photon candidate like the one described in section 4.1.1 (further requiring the photon's isolation be less than 2.0 GeV) as well as an electron capable of faking a photon as described in section 4.1.2.

We then weight the events by the probability of the electron to fake a photon divided by the number of electrons capable of faking a photon.

4.6 Double Counting of Jets Faking Photons, and Jets Mistagged as B-jets

To measure the amount of jets faking photons and jets misidentified as b-jets

requires substantial $\not{E}_T$, and a tight lepton. The overlap comes from events which also have a photon candidate like the one described in section 4.1.1 (further requiring the photon's isolation be less than 2.0 GeV) as well as a taggable jet capable of being tagged as a b-jet as described in section 4.2.

We then weight the events by the probability of the jets in the event to be mistagged as a b-jet.

4.7 Double Counting of Electrons Faking Photons, and Jets Mistagged as B-jets

To measure the amount of electrons faking photons and jets misidentified as b-jets

requires substantial $\not{E}_T$, and a tight lepton. The overlap comes from events which also have a photon candidate like the one described in section 4.1.2 as well as a taggable jet capable of being tagged as a b-jet as described in section 4.2.

The events are then weighted by the probability of the electrons in the event to be misidentified as photons divided by the number of electrons capable of faking photons. We then further weight these events by the probability of a jet to be misidentified as a b-jet.

4.8 Double Counting of QCD fakes, and Jets Mistagged as B-jets

To measure the amount of double counting due to jets mistagged a b-jets, and jets which fake leptons, we require a sample of an anti-electron, jets capable of being mistagged, substantial $\not{E}_T$, and a tight photon. In this case, the $\not{E}_T$ is correct by muons, and jets, and uncorrected by the anti-electron.

If the anti-electron were not designated as such, then it would have passed the selection criteria of a jet, and hence the $\not{E}_T$ would have been corrected by it.

These events are then weighted by the probability of a jet to be misidentified as a b-jet. The anti-electron must have a track isolation less than 4 GeV to enter our selection criteria for $\ell\gamma\not{E}_T b$. To enter the selection criteria for $t\bar{t}\gamma$ the event must further have $H_T > 200$ GeV and more than 2 jets (not including the anti-electron).

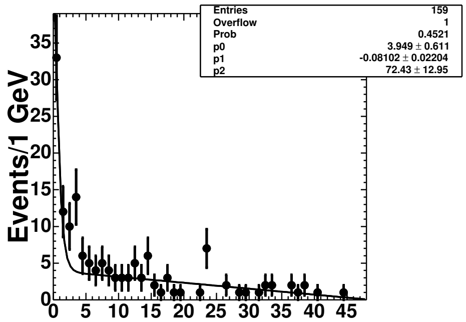
4.9 Double Counting of QCD fakes, and Jets Faking Photons

The procedure described in section 4.1.1 is repeated, with the new requirement that we have an anti-electron instead of a tight lepton. We still require a b-jet and substantial $\not{E}_T$ uncorrected due to the anti-electron. The reasoning is described in 4.8. We then look for events that have a photon candidate with Calorimeter Isolation less than 2 GeV, and require the anti-electron to have Track Isolation less than 4 GeV, to pass the $\ell\gamma\not{E}_T b$ selection criteria. We further require H_T greater than 200 GeV and 3 or more jets (not including the anti-electron) to enter into the $t\bar{t}\gamma$ selection criteria.

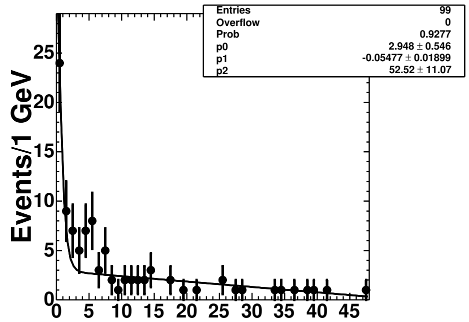
4.10 Double Counting of QCD fakes, and Electrons Faking Photons

The procedure described in section 4.1.2 is repeated, with the new requirement that we have an anti-electron instead of a tight lepton. We still require a b-jet, electrons capable of faking photons, and substantial $\not{E}_T$ uncorrected due to the anti-electron. The reasoning for this is described in 4.8. We require the anti-electron to have Track Isolation less than 4 GeV, to pass the $\ell\gamma\not{E}_T b$ selection criteria. We further require H_T greater than 200 GeV and 3 or more jets (not including the anti-electron) to enter into the $t\bar{t}\gamma$ selection criteria. These events are then weighted by the probabiliy of the electrons to fake a photon, divided by the number of electrons capable of faking a photon.

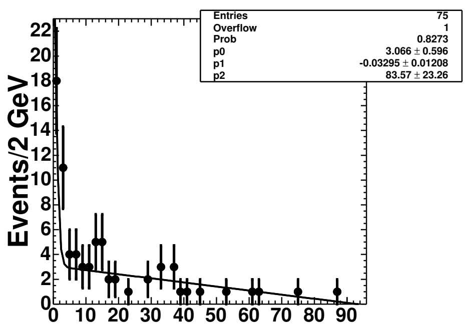
5 Event Display



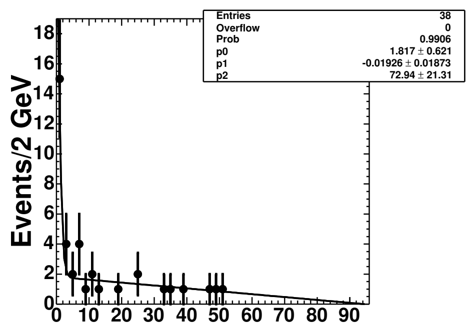
(a) Calorimeter Isolation of Photons Candidates ($e\gamma \not{E}_{\mathrm{T}} b$)



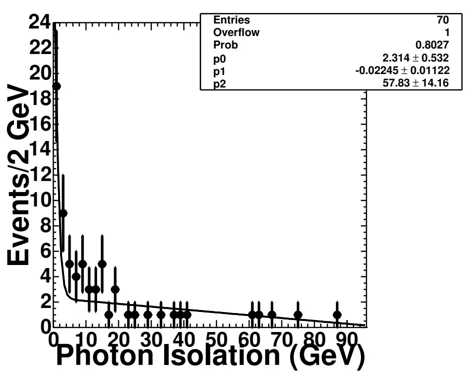
(b) Calorimeter Isolation of Photons Candidates ($\mu\gamma \not{E}_{\mathrm{T}} b$)



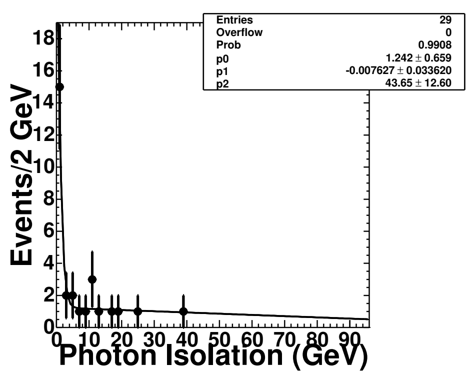
(c) Calorimeter Isolation of Photons Candidates ($t\bar{t}\gamma$ (e))



(d) Calorimeter Isolation of Photons Candidates ($t\bar{t}\gamma$ (μ))



(e) Calorimeter Isolation of Photons Candidates ($t\bar{t}\gamma$ (e))



(f) Calorimeter Isolation of Photons Candidates ($t\bar{t}\gamma$ (μ))

Figure 4.1: The method and data used to estimate the number of background events from jets misidentified as photons. For each of the four samples, $e\gamma \not{E}_{\mathrm{T}} b$ (left top), $t\bar{t}\gamma$ (e channel, right top), $\mu\gamma \not{E}_{\mathrm{T}} b$ (left bottom), and $t\bar{t}\gamma$ (μ channel, right bottom), the number of events is plotted versus the total (electromagnetic plus hadronic) calorimeter energy, $\mathrm{E}_{\mathrm{T}}^{Iso}$, in a cone in η-ϕ space around the photon. This distribution is then fitted to the shape measured for electrons from $\mathrm{Z}^0 \rightarrow e^+e^-$ decays plus a linear background.

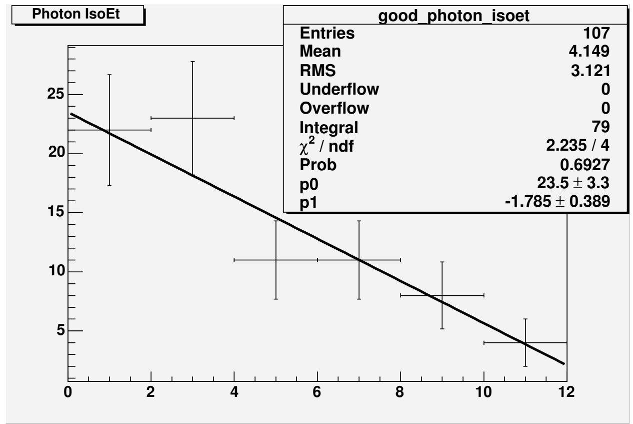
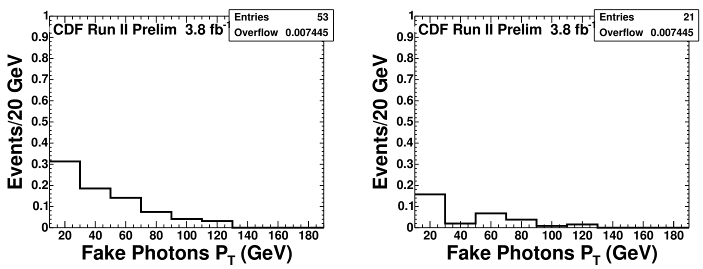
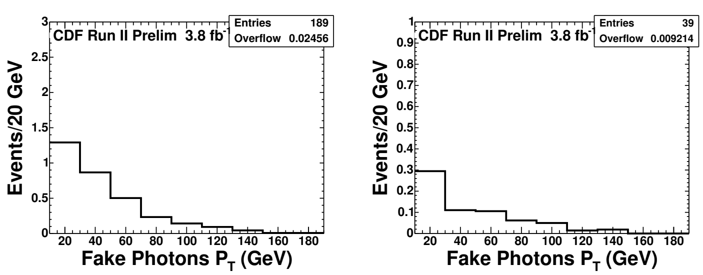


Figure 4.2: The distribution in the total calorimeter energy, E_T^{Iso}, in a cone in η-ϕ space around the fake photon candidate. This distribution is then fitted with a linear function.



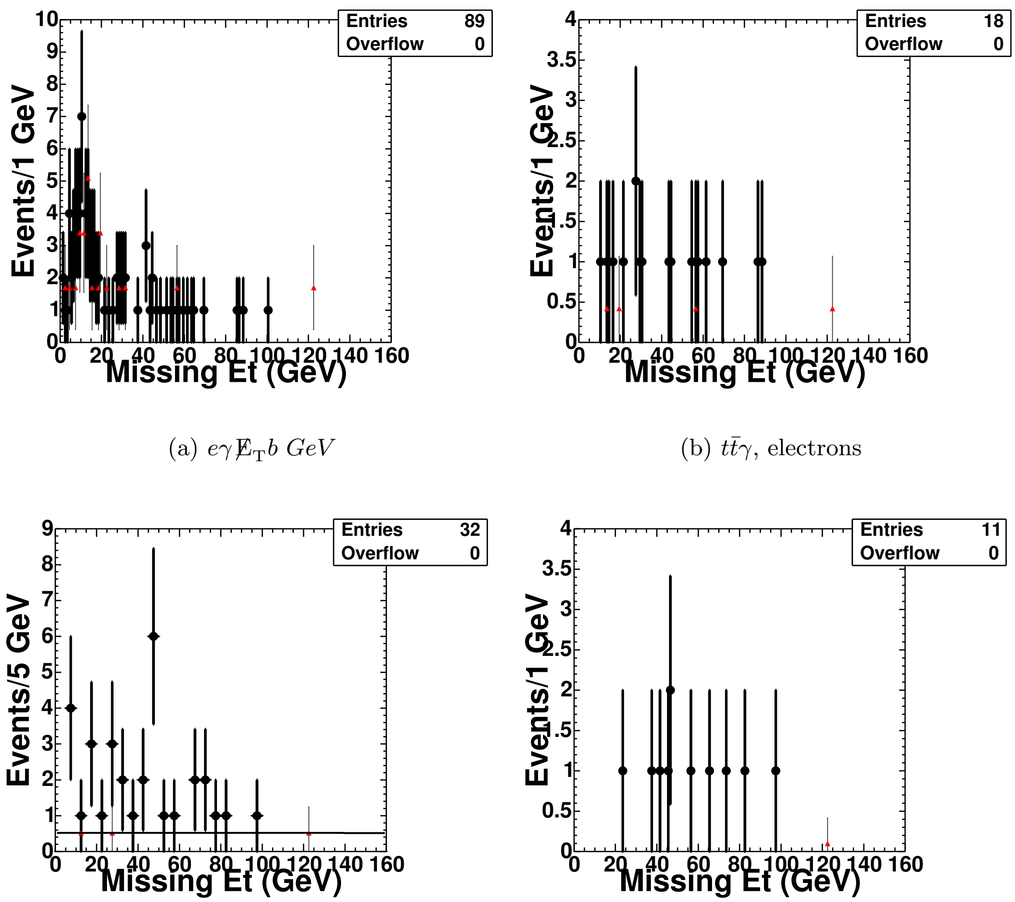
(a) $\mu\gamma\not\!\!E_T b$ (b) $t\bar{t}\gamma$, muons

Figure 4.3: Spectrum of electrons faking photons used to calculate $e \to \gamma$ fake rate. We selected $ee\not\!\!E_T b$ events, and then applied $e \to \gamma$ fake rate [14].



(a) $e\gamma\not\!\!E_T b$ (b) $t\bar{t}\gamma$, electrons

Figure 4.4: Spectrum of electrons faking photons used to calculate $e \to \gamma$ fake rate. We selected $\mu e\not\!\!E_T b$ events, and then applied $e \to \gamma$ fake rate [14].



(a) $e\gamma \not\!\!E_T b$ GeV

(b) $t\bar{t}\gamma$, electrons

(c) $\mu\gamma \not\!\!E_T b$

(d) $t\bar{t}\gamma$, muons

Figure 4.5: Spectrum of anti-electrons used to calculate QCD fakes. We selected events with a bjet, a photon, and an anti-electron, and then scaled its $\not\!\!E_T$ distribution below 20 GeV to those distributions of $\ell\gamma \not\!\!E_T b$ without a $\not\!\!E_T$ cut.

We show in figure 5.1 a signature event for $t\bar{t}\gamma$. This event has a tight photon, has 2 b-tagged jets, substantial $\not{E}_T$, and the H_T of the event is large at 206.8 GeV, as well as tight lepton with track isolation less than 4 GeV. This is precisely the type of signature that we would expect from a $t\bar{t}\gamma$ type event.

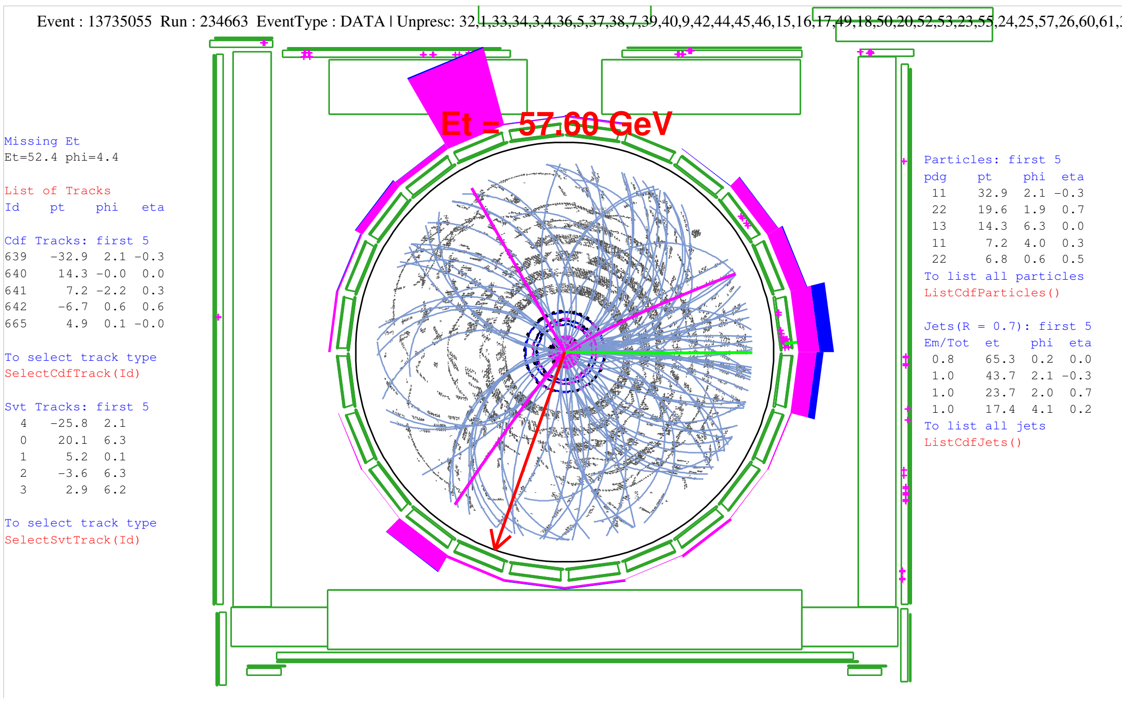


Figure 5.1: A hight pt electron event (run 234663 event 13735055) with 2 b-tagged jets, high ht, and electron track isolation less than 4 GeV. The H_T of the event is 206.8 GeV, and the $\not{E}_T$ is 56.8 GeV. There are 3 high p_T jets. The leading lepton p_T is 39.1 GeV, and the photon has a p_T of 18.7 GeV.

6 Results

In this section we present our results for each of our selection criteria, our observed amount of data in 4.8fb^{-1}. We see excellent agreement across all three categories. The contribution to double counting for each of the pairs of data-driven backgrounds can be found in Table A.8, A.9, and A.10.

CDF Run II Preliminary, 4.8fb^{-1}			
Lepton + Photon + $\not{E}_T$ + b Events, Isolated Leptons			
Standard Model 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	$5.23 \pm 0.19 \pm 0.94(sys)$	$3.94 \pm 0.17 \pm 0.71$ (sys.)	9.17 ± 1.67
$t\bar{t}\gamma$ dileptonic	$2.98 \pm 0.085 \pm 0.54(sys)$	$2.27 \pm 0.074 \pm 0.41$ (sys.)	5.25 ± 0.96
$W^{\pm}c\gamma$	$1.76 \pm 0.31 \pm 0.18(sys)$	$1.64 \pm 0.30 \pm 0.17(sys)$	3.40 ± 0.55
$W^{\pm}cc\gamma$	$0.19 \pm 0.090 \pm 0.019(sys)$	$0.50 \pm 0.15 \pm 0.053(sys)$	0.69 ± 0.18
$W^{\pm}bb\gamma$	$1.52 \pm 0.20 \pm 0.16(sys)$	$1.01 \pm 0.16 \pm 0.11(sys)$	2.53 ± 0.37
WZ	$0.18 \pm 0.083 \pm 0.023(sys)$	$0.057 \pm 0.047 \pm 0.0074(sys)$	0.23 ± 0.095
WW	$0.26 \pm 0.045 \pm 0.034(sys)$	$0.22 \pm 0.041 \pm 0.029(sys)$	0.48 ± 0.085
$\tau \rightarrow \gamma$ fake	$0.29 \pm 0.078 \pm 0.038(sys)$	$0.26 \pm 0.074 \pm 0.034(sys)$	0.55 ± 0.10
Jet faking γ ($ej\not{E}_T b, j \rightarrow \gamma$)	8.3 ± 1.3	5.5 ± 1.1	13.80 ± 1.70
MisTags	11.99 ± 1.07	8.04 ± 0.74	20.03 ± 1.71
QCD(Jets faking ℓ and $\not{E}_T$)	6.9 ± 3.10	0.0 ± 1	6.90 ± 4.10
$ee\not{E}_T b$, $e \rightarrow \gamma$	4.07 ± 0.59	–	4.07 ± 0.59
$\mu e\not{E}_T b$, $e \rightarrow \gamma$	–	0.87 ± 0.16	0.87 ± 0.16
Total DC	4.20	2.99	7.190
Total SM Prediction	$39.47 \pm 3.76(tot)$	$21.32 \pm 1.92(tot)$	$60.78 \pm 5.20(tot)$
Observed in Data	38	23	61.00

Table 6.1: MC samples have been scaled to 4.8fb^{-1}. Data driven backgrounds have been found in the method described in previous sections.

CDF Run II Preliminary, 4.8fb^{-1}			
$t\bar{t}\gamma$, Isolated Leptons			
Standard Model Source	$e\gamma b\not{E}_T$	$\mu\gamma b\not{E}_T$	$(e+\mu)\gamma b\not{E}_T$
$t\bar{t}\gamma(semileptonic)$	$5.02 \pm 0.19 \pm 0.90(sys)$	$3.82 \pm 0.17 \pm 0.69(sys)$	8.84 ± 1.61
$t\bar{t}\gamma(dileptonic)$	$1.28 \pm 0.056 \pm 0.23(sys)$	$0.98 \pm 0.049 \pm 0.18(sys)$	2.26 ± 0.42
$W^{\pm}c\gamma$	$0 \pm 0.054 \pm 0(sys)$	$0 \pm 0.054 \pm 0(sys)$	0 ± 0.070
$W^{\pm}cc\gamma$	$0 \pm 0.042 \pm 0(sys)$	$0.032 \pm 0.037 \pm 0.0034(sys)$	0.03 ± 0.050
$W^{\pm}bb\gamma$	$0.14 \pm 0.061 \pm 0.014(sys)$	$0.044 \pm 0.034 \pm 0.0046(sys)$	0.18 ± 0.061
WZ	$0.035 \pm 0.037 \pm 0.0046(sys)$	$0 \pm 0.038 \pm 0(sys)$	0.03 ± 0.050
WW	$0.065 \pm 0.022 \pm 0.0085(sys)$	$0.057 \pm 0.021 \pm 0.0074(sys)$	0.12 ± 0.032
$\tau \rightarrow \gamma$ fake	$0.17 \pm 0.060 \pm 0.022(sys)$	$0.068 \pm 0.038 \pm 0.0088(sys)$	0.23 ± 0.076
Jet faking γ ($ej\not{E}_T b, j \rightarrow \gamma$)	6.8 ± 1.2	4.3 ± 1.3	11.10 ± 1.76
MisTags	2.08 ± 0.17	1.62 ± 0.13	3.70 ± 0.30
QCD(Jets faking ℓ and $\not{E}_T$)	0.8 ± 0.60	0.0 ± 1	0.80 ± 1.60
$ee\not{E}_T b$, $e \rightarrow \gamma$	0.88 ± 0.19	–	0.88 ± 0.19
$\mu e\not{E}_T b$, $e \rightarrow \gamma$	–	0.36 ± 0.089	0.36 ± 0.089
Total Amount of DC	1.29	1.26	2.550
Total SM Prediction	$15.99 \pm 1.41(tot)$	$10.02 \pm 1.68(tot)$	$25.98 \pm 2.45(tot)$
Observed in Data	15	11	26.00

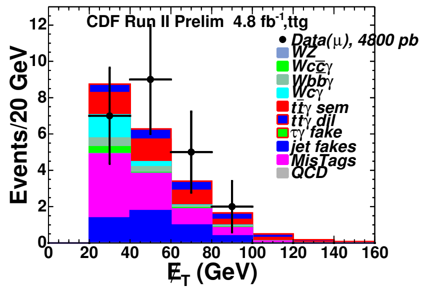
Table 6.2: MC samples have been scaled to 4.8fb^{-1}. All other Data-driven numbers have been measured in the manner described in earlier sections.

CDF Run II Preliminary, 4.8fb^{-1}			
$t\bar{t}\gamma$, Isolated Leptons, Tight Chi2 on Photons			
Standard Model Source	$e\gamma b\not{E}_T$	$\mu\gamma b\not{E}_T$	$(e+\mu)\gamma b\not{E}_T$
$t\bar{t}\gamma(semileptonic)$	$4.76 \pm 0.18 \pm 0.86(sys)$	$3.63 \pm 0.16 \pm 0.65(sys)$	8.39 ± 1.53
$t\bar{t}\gamma(dileptonic)$	$1.23 \pm 0.055 \pm 0.22(sys)$	$0.93 \pm 0.048 \pm 0.17(sys)$	2.16 ± 0.40
$W^{\pm}c\gamma$	$0 \pm 0.054 \pm 0(sys)$	$0 \pm 0.054 \pm 0(sys)$	0 ± 0.070
$W^{\pm}cc\gamma$	$0 \pm 0.042 \pm 0(sys)$	$0.032 \pm 0.037 \pm 0.0034(sys)$	0.03 ± 0.050
$W^{\pm}bb\gamma$	$0.14 \pm 0.061 \pm 0.014(sys)$	$0.044 \pm 0.034 \pm 0.0046(sys)$	0.18 ± 0.061
WZ	$0.035 \pm 0.037 \pm 0.0046(sys)$	$0 \pm 0.038 \pm 0(sys)$	0.03 ± 0.050
WW	$0.065 \pm 0.022 \pm 0.0085(sys)$	$0.050 \pm 0.020 \pm 0.0065(sys)$	0.11 ± 0.022
$\tau \rightarrow \gamma$ fake	$0.13 \pm 0.053 \pm 0.017(sys)$	$0.068 \pm 0.038 \pm 0.0088(sys)$	0.19 ± 0.063
Jet faking γ $(ej\not{E}_T b, j\rightarrow\gamma)$	4.6 ± 1.1	2.5 ± 1.3	7.10 ± 1.70
MisTags	2.06 ± 0.16	1.49 ± 0.12	3.55 ± 0.28
QCD(Jets faking ℓ and $\not{E}_T$)	0.8 ± 0.60	0.0 ± 1	0.80 ± 1.60
$ee\not{E}_T b$, $e\rightarrow\gamma$	0.87 ± 0.19	–	0.87 ± 0.19
$\mu e\not{E}_T b$, $e\rightarrow\gamma$	–	0.36 ± 0.089	0.36 ± 0.089
Total Amount of DC	1.10	1.26	2.360
Total SM Prediction	$13.60 \pm 1.32(tot)$	$7.84 \pm 1.68(tot)$	$21.41 \pm 2.40(tot)$
Observed in Data	15	11	26.00

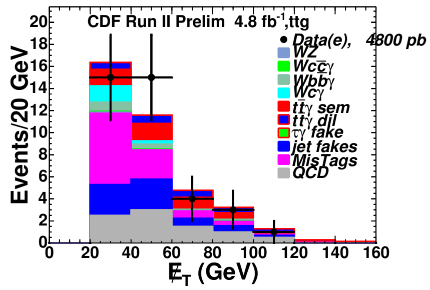
Table 6.3: MC samples have been scaled to 4.8fb^{-1}. All other Data-driven numbers have been measured in the manner described in earlier sections.

CDF Run II Preliminary, 4.8fb^{-1}			
$t\bar{t}$, Isolated Leptons, 3 or more jets, $H_T > 200$ GeV			
Standard Model Source	$eb\not{E}_T$	$\mu b\not{E}_T$	$(e+\mu)b\not{E}_T$
$t\bar{t}(ttop75)$	$1118.25 \pm 2.76 \pm 145.37(sys)$	$860.04 \pm 2.42 \pm 111.81(sys)$	$1978.29 \pm 257.21(sy$
WW	$17.07 \pm 0.36 \pm 2.22(sys)$	$12.81 \pm 0.31 \pm 1.67(sys)$	29.88 ± 3.92
WZ	$5.20 \pm 0.11 \pm 0.68(sys)$	$3.89 \pm 0.094 \pm 0.51(sys)$	9.09 ± 1.20
ZZ	$2.35 \pm 0.073 \pm 0.31(sys)$	$1.66 \pm 0.061 \pm 0.22(sys)$	4.01 ± 0.54
$W^{\pm}bb + 0p$	$7.70 \pm 0.27 \pm 1.00(sys)$	$5.73 \pm 0.23 \pm 0.74(sys)$	13.43 ± 1.77
$W^{\pm}bb + 1p$	$30.66 \pm 0.29 \pm 3.99(sys)$	$22.04 \pm 0.25 \pm 2.87(sys)$	52.70 ± 6.87
$W^{\pm}bb + 2p$	$46.97 \pm 0.21 \pm 6.11(sys)$	$34.77 \pm 0.18 \pm 4.52(sys)$	81.74 ± 10.63
MisTags	$663.18 \pm 6.44 \pm 53.05(sys)$	$387.83 \pm 4.63 \pm 31.03(sys)$	1051.01 ± 84.45
QCD (jets faking l and $\not{E}_T$)	636.5 ± 44.6	25.1 ± 5.3	661.60 ± 49.90
Total Amount of DC	17.38	1.46	18.840
Total SM Prediction	$2510.50 \pm 154.94(tot)$	$1352.41 \pm 116.18(tot)$	$3862.91 \pm 270.92(to$
Observed in Data	2450	1525	3975.00

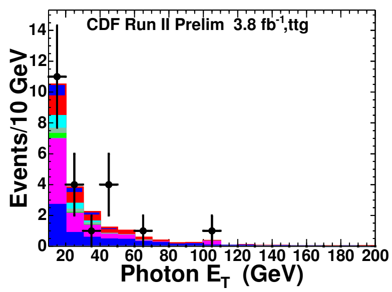
Table 6.4: MC samples have been scaled to 4.8fb^{-1}. All other Data-driven numbers have been measured in the manner described in earlier sections.



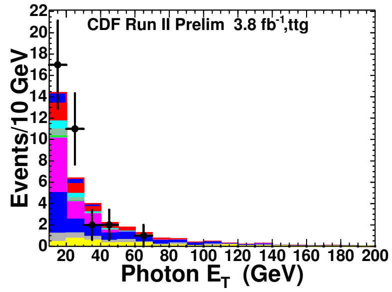
(a) $\mu\gamma\not\!\!E_{\rm T}b$



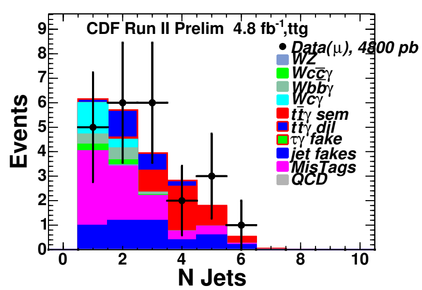
(b) $e\gamma\not\!\!E_{\rm T}b$



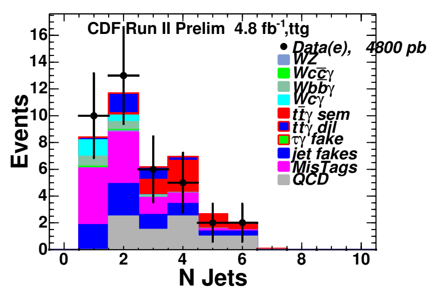
(c) $\mu\gamma\not\!\!E_{\rm T}b$



(d) $e\gamma\not\!\!E_{\rm T}b$

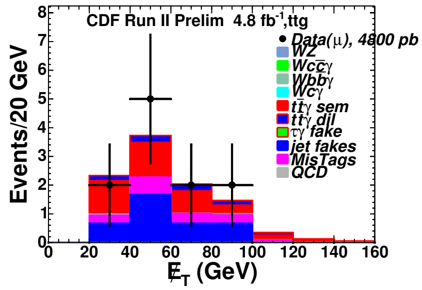


(e) $\mu\gamma\not\!\!E_{\rm T}b$

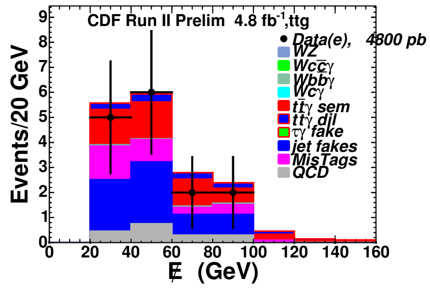


(f) $e\gamma\not\!\!E_{\rm T}b$

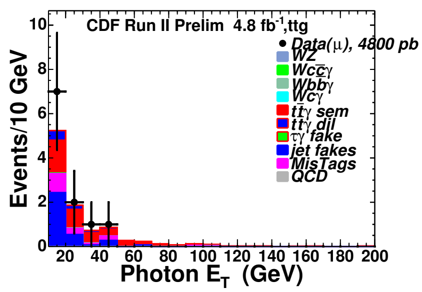
Figure 6.1: Spectrum of $\not\!\!E_{\rm T}$ distributions for $\ell\gamma\not\!\!E_{\rm T}b$ events



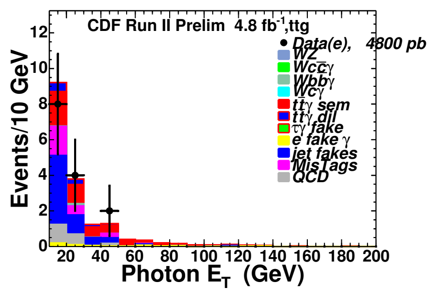
(a) $t\bar{t}\gamma(\mu)$



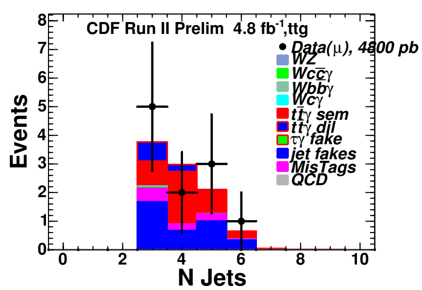
(b) $t\bar{t}\gamma(e)$



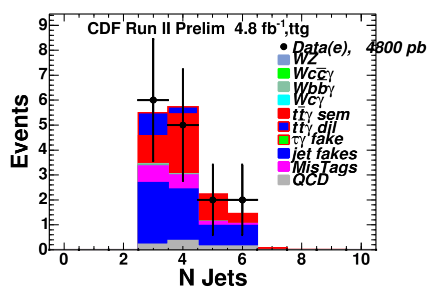
(c) $t\bar{t}\gamma(mu)$



(d) $t\bar{t}\gamma(e)$



(e) $\mu\gamma\not{E}_\mathrm{T}b$



(f) $e\gamma\not{E}_\mathrm{T}b$

Figure 6.2: Spectrum of $\not{E}_\mathrm{T}$ distributions for $t\bar{t}\gamma$ events

7 Conclusions

We presented a search for anomalous production of the signature $\ell + \gamma + b - quark + \not{E}_{\mathrm{T}}$ and a search for $t\bar{t} + \gamma$ events produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV using data taken with the CDF detector in Run II at the Tevatron.

We measured $t\bar{t}\gamma$ cross-section

$$\sigma_{t\bar{t}\gamma} = \frac{(26.00\pm5.09)-(14.88\pm2.44)}{4.8\mathrm{fb}^{-1}(0.0304\pm\mathrm{x.xx})} = .076 \pm .039pb$$

compared to $\sigma_{semileptonic\ t\bar{t}\gamma} = 0.080 \pm 0.012pb$ obtained from MadGraph.

We measured the $t\bar{t}$ cross-section to be $7.33 \pm .22$ pb.

We also measured a ratio of the $t\bar{t}\gamma$ cross-section to the $t\bar{t}$ cross-section to be $xxx \pm xxx$.

8 Acknowledgments

We thank Uli Baur for invaluable help with our analysis and help for generating MC processes. We thank Frank Petriello for his advices on k-factor for $t\bar{t}\gamma$ process. We thank Tim Steltzer, Steve Mrenna, and Fabio Maltoni for their support and development for MadGraph and Pythia and Soushi Tsuno for help with our MC. Alexander Paramonov helped us to get started on the TTGNtuple. We also would like to thank our CDF collaborators Ray Culbertson, ... for their many contributions.

A Appendices

A.1 List Of Lepton-Photon-$\not\!\!E_T$-B Events (1.9 fb^{-1})

run/event	$P_T(\ell)$	$\not\!\!E_T$	M($\ell\not\!\!E_T$)	$P_T(\gamma)$	M($W\gamma$)	H_T	$P_T(\ell\gamma)$	M($\ell\gamma$)	jets	b tags
196879/3659187	22.03	44.62	44.46	40.89	77.91	272.77	62.83	21.71	4	1
196892/77507	37.88	41.17	74.72	14.71	89.41	138.17	52.04	43.56	1	1
197321/1409712	27.36	57.74	51.78	20.42	62.56	323.96	46.91	18.62	5	1
193396/1050006	39.31	86.54	56.02	12.25	74.13	349.52	35.89	37.30	4	2
207488/2477561	73.01	89.01	6.43	13.62	23.96	413.75	84.99	17.48	4	2
209850/2864478	40.56	59.57	70.66	62.93	159.08	259.32	73.28	85.57	2	1
222835/7771229	66.94	21.69	41.06	35.33	109.30	243.99	40.11	94.72	3	1
223494/10133378	30.90	28.91	56.38	10.34	63.60	91.90	39.49	12.23	1	1
227377/11344663	53.97	29.02	78.48	10.23	86.21	116.46	63.48	24.03	1	1
231294/19688018	28.33	21.17	5.52	10.38	26.43	117.61	34.20	22.50	2	1
232226/1187677	37.45	23.52	59.19	32.60	86.34	134.06	55.72	68.69	1	1
233110/55577	88.95	29.68	96.10	10.04	105.16	187.45	90.74	39.83	1	1
233798/1492655	51.20	29.35	59.20	43.12	123.08	206.84	30.16	89.42	3	1
234663/13735055	39.13	56.83	81.25	18.65	100.18	206.77	57.63	29.17	3	2
236965/6459811	44.66	44.31	62.77	27.05	84.38	200.71	45.36	66.81	2	1
237478/34732412	28.46	28.07	7.68	27.26	28.46	219.67	53.49	20.93	3	1

Table A.1: List Of $e\gamma\not\!\!E_T b$ Events

run/event	$P_T(\ell)$	$\not\!\!E_T$	M($\ell\not\!\!E_T$)	$P_T(\gamma)$	M($W\gamma$)	H_T	$P_T(\ell\gamma)$	M($\ell\gamma$)	jets	b tags
160591/847583	70.10	23.20	26.48	11.11	28.70	282.57	80.61	12.99	5	1
155996/1456579	27.42	31.06	51.75	21.88	74.81	107.33	46.60	26.19	1	1
197287/7739046	48.69	82.20	21.88	37.14	78.33	385.24	77.19	63.27	3	1
199620/711826	46.02	27.41	70.38	107.97	158.19	321.51	61.95	182.40	2	1
195343/9039070	27.59	53.02	68.64	45.81	97.28	213.05	67.14	37.49	3	1
206828/3127590	122.91	45.52	50.90	17.39	81.35	353.99	132.36	49.65	3	2
209532/76676	26.49	65.50	15.64	28.99	92.49	194.06	19.15	52.09	1	1
209819/2062462	46.11	72.74	7.19	16.51	17.70	342.24	61.45	15.28	3	1
209862/445276	37.65	47.25	55.31	13.75	84.58	332.52	31.44	47.38	3	1
218692/305924	22.25	32.01	49.37	46.57	94.67	162.16	34.96	59.28	3	1
221201/7636658	68.58	47.08	67.79	12.87	98.84	367.00	55.75	60.49	6	1
221723/9869061	22.44	98.04	19.44	13.77	67.72	351.00	27.08	32.02	5	3

Table A.2: List Of $\mu\gamma\not\!\!E_T b$ Events

A.2 List of Lepton-Photon-$\not\!\!E_T$-B events (4.8 fb^{-1})

```
The stripped TTG ntuple begins with stripping the StNtuple to events which
contain at least a loose lepton, or an anti-electron.
```

run/event	$P_T(\ell)$	$\not{E}_T$	M($\ell\not{E}_T$)	$P_T(\gamma)$	M($W\gamma$)	H_T	$P_T(\ell\gamma)$	M($\ell\gamma$)	jets	b tags
185594/10091587	21.29	65.06	21.75	24.79	40.69	311.21	38.38	25.49	5	1
155996/1456579	27.42	31.08	51.74	21.85	74.79	107.69	46.57	26.22	1	1
160591/847583	70.10	23.20	26.47	11.11	28.70	281.76	80.61	12.99	5	1
195343/9039070	27.59	52.90	68.58	45.80	97.23	211.81	67.14	37.50	3	1
199620/711826	46.02	27.19	70.11	107.92	158.02	319.64	61.90	182.40	2	1
197287/7739046	48.69	82.00	21.85	37.12	78.23	383.11	77.17	63.35	3	1
209532/76676	26.49	65.56	15.61	29.06	92.64	193.33	19.18	52.15	1	1
209819/2062462	46.11	73.17	7.02	16.58	17.75	342.23	61.52	15.31	3	1
209862/445276	37.65	46.94	54.81	13.77	84.22	331.13	31.44	47.42	3	1
221723/9869061	22.44	97.90	19.46	13.77	67.70	349.34	27.08	32.02	5	3
218692/305924	22.25	31.93	49.34	46.57	94.56	161.22	34.96	59.28	3	1
221201/7636658	68.58	46.85	68.10	12.87	98.95	364.19	55.75	60.48	6	1
206828/3127590	122.91	45.43	51.12	17.39	81.51	351.43	132.36	49.64	3	2
245448/3767387	29.61	21.24	8.11	25.23	71.26	162.82	5.59	55.37	2	1
239906/2521891	41.07	46.13	66.57	16.23	82.47	160.55	56.47	10.44	1	1
242648/1139872	44.89	46.84	79.79	69.34	140.42	238.25	109.71	32.29	1	1
244537/3194828	34.41	44.86	7.19	88.39	166.53	190.59	56.57	122.31	1	1
244676/30558295	29.31	77.84	95.43	14.14	104.44	370.21	16.55	44.87	2	1
255090/1491384	20.43	42.65	41.60	11.35	51.02	137.90	17.18	26.75	2	1
256581/55740	49.24	41.55	54.19	26.00	69.39	215.71	75.07	18.34	3	1
259189/993053	36.88	57.99	10.15	48.52	13.39	291.91	85.35	26.40	2	1
259673/16312239	48.05	37.57	82.36	12.39	95.90	324.10	53.52	43.78	4	1
262776/10750406	95.68	30.55	11.83	19.00	34.94	356.77	111.63	26.80	2	1
263877/861995	43.73	47.32	90.43	42.76	129.47	246.40	78.99	52.29	2	1
265582/12252209	31.93	25.96	55.86	19.05	68.99	104.27	43.55	40.91	1	1
265865/1871442	81.73	26.37	35.47	19.97	46.17	274.90	100.54	20.47	3	1
273747/7624925	53.84	41.04	67.50	22.66	83.87	196.29	75.95	22.05	1	1
275804/18282441	36.67	27.67	63.50	14.83	76.66	398.56	36.32	44.16	5	1
275728/4876317	64.15	41.17	76.86	30.98	129.09	177.44	51.82	90.94	1	1
277505/3178590	32.92	64.37	54.22	12.73	58.62	210.24	40.01	32.67	2	1

Table A.3: List Of $\mu\gamma\not{E}_T b$ Events 4.8 fb^{-1}

```
We then further strip the TTG ntuple requiring one of the following
groups of objects must be in an event:
a tight lepton and a loose lepton
tight photon and loose lepton
loose lepton and met > 15
antielectron + a photon
antielectron + a bjet
met > 15 and bjet > 0
met > 15 and a tight photon
loose lepton and a bjet
```

run/event	$P_T(\ell)$	$\not\!\!E_{\rm T}$	M($\ell\not\!\!E_{\rm T}$)	$P_T(\gamma)$	M($W\gamma$)	H_T	$P_T(\ell\gamma)$	M($\ell\gamma$)	jets	b tags
185594/10091587	21.29	65.06	21.75	24.79	40.69	311.21	38.38	25.49	5	1
155996/1456579	27.42	31.08	51.74	21.85	74.79	107.69	46.57	26.22	1	1
160591/847583	70.10	23.20	26.47	11.11	28.70	281.76	80.61	12.99	5	1
195343/9039070	27.59	52.90	68.58	45.80	97.23	211.81	67.14	37.50	3	1
199620/711826	46.02	27.19	70.11	107.92	158.02	319.64	61.90	182.40	2	1
197287/7739046	48.69	82.00	21.85	37.12	78.23	383.11	77.17	63.35	3	1
209532/76676	26.49	65.56	15.61	29.06	92.64	193.33	19.18	52.15	1	1
209819/2062462	46.11	73.17	7.02	16.58	17.75	342.23	61.52	15.31	3	1
209862/445276	37.65	46.94	54.81	13.77	84.22	331.13	31.44	47.42	3	1
221723/9869061	22.44	97.90	19.46	13.77	67.70	349.34	27.08	32.02	5	3
218692/305924	22.25	31.93	49.34	46.57	94.56	161.22	34.96	59.28	3	1
221201/7636658	68.58	46.85	68.10	12.87	98.95	364.19	55.75	60.48	6	1
206828/3127590	122.91	45.43	51.12	17.39	81.51	351.43	132.36	49.64	3	2
245448/3767387	29.61	21.24	8.11	25.23	71.26	162.82	5.59	55.37	2	1
239906/2521891	41.07	46.13	66.57	16.23	82.47	160.55	56.47	10.44	1	1
242648/1139872	44.89	46.84	79.79	69.34	140.42	238.25	109.71	32.29	1	1
244537/3194828	34.41	44.86	7.19	88.39	166.53	190.59	56.57	122.31	1	1
244676/30558295	29.31	77.84	95.43	14.14	104.44	370.21	16.55	44.87	2	1
255090/1491384	20.43	42.65	41.60	11.35	51.02	137.90	17.18	26.75	2	1
256581/55740	49.24	41.55	54.19	26.00	69.39	215.71	75.07	18.34	3	1
259189/993053	36.88	57.99	10.15	48.52	13.39	291.91	85.35	26.40	2	1
259673/16312239	48.05	37.57	82.36	12.39	95.90	324.10	53.52	43.78	4	1
262776/10750406	95.68	30.55	11.83	19.00	34.94	356.77	111.63	26.80	2	1
263877/861995	43.73	47.32	90.43	42.76	129.47	246.40	78.99	52.29	2	1
265582/12252209	31.93	25.96	55.86	19.05	68.99	104.27	43.55	40.91	1	1
265865/1871442	81.73	26.37	35.47	19.97	46.17	274.90	100.54	20.47	3	1
273747/7624925	53.84	41.04	67.50	22.66	83.87	196.29	75.95	22.05	1	1
275804/18282441	36.67	27.67	63.50	14.83	76.66	398.56	36.32	44.16	5	1
275728/4876317	64.15	41.17	76.86	30.98	129.09	177.44	51.82	90.94	1	1
277505/3178590	32.92	64.37	54.22	12.73	58.62	210.24	40.01	32.67	2	1

Table A.4: List Of $e\gamma\not\!\!E_{\rm T}b$ Events 4.8 fb^{-1}

`bjet and a photon.`

A.3 TTGNtupler package

The TTGNtupler package is an ntupler built on top of the Stntuple framework using its classes and methods to access information about the data.

When first running the package over the Stntuples we produce TTGNtuples on the CDF CAF and saved them on the UChicago Clusters. We show the initial number of events in the Stntuple as well as the amount of events which have at least one loose lepton or one anti-electron.

We have made the following cross-checks against UCNtuple to verify the TTGNtupler code,

Dataset	Stntuple	N Events	N Stripped	Begin Run	End Run	int.lumi (pb)
bhel0d	bhelbd	26,499,561	3,338,119	138425	186598	520
bhel0h	bhelbh	19,813,851	2,831,808	191208	203799	460
bhel0i	bhelbi	28,940,435	3,958,586	203819	228596	730
bhel0i, bhel0j	bhelbij	11,588,610	1,483,459	228664	233111	290
bhel0j	bhelbj	32,259,040	3,964,960	233133	246231	760
bhel0k	bhelbk	37,161,882	2,917,732	252836	261005	380
bhel0m	bhelbm	110,622,129	7,166,756	261119	271047	1480
bhmu0d	bhmubd	6,629,080	785,803	138425	186598	520
bhmu0h	bhmubh	5,740,083	629,063	191208	203799	460
bhmu0i	bhmubi	8,853,061	972,538	203819	228596	730
bhel0i, bhel0j	bhelbij	4,712,958	452,395	228664	233111	290
bhmu0j	bhmubj	12,578,391	1,216,406	233133	246231	760
bhmu0k	bhmubk	32,847,648	1,620,320	252836	261005	380
bhmu0m	bhmubm	98,161,571	3,362,278	261119	271047	1480

Table A.5: Results of isolating events with at least one loose lepton or anti-electron from raw Stntuples

for data periods bhel0h, bhmu0h, bhel0d, and bhmu0d:

- have compared number of dilepton events in both electron and muon data streams
- checked further across all six combinations of CMX, CMUP and stubless muons
- and for Z's decaying to both central electrons, or one central and one plug electron
- compared number of dilepton and photon events
- compared number of lepton, photon, and $\not\!\!E_{\rm T}$ events

For the first 1.78 fb^{-1} we further checked

- repeated comparisons mentioned above
- the run and event numbers of all $\ell\gamma\not\!\!E_{\rm T}b$ events

We have compared event yields obtained in the UCNtuple and in the TTGNtupler for the first 1.78 fb^{-1}, and results are shown in Tables A.7

A.4 Discussion on k-factor for $t\bar{t}\gamma$ MadGraph Samples

We have put here a feedback/discussion we have received from Uli Baur and Frank Petriello.

Uli Baur on k-factor:

"well, the NLO QCD corrections to ttbar-gamma still have not been calculated. However, those for ttbar-Z have recently been computed. Except for the mass of the Z, the two processes are very similar. So I would guess that the k-factors and the remaining scale uncertainty are similar.

I think the best procedure right now is to take the k-factor from ttbar-Z.

The people who calculated the NLO QCD corrections to ttbar-Z are Frank Petriello from Madison and collaborators. They have a couple of recent papers on the archive. One is for qqbar $->$

Dataset	TTG Location	Stripped Location
bhelbd	/cdf/s13/auerbach/cafTest/bhelbd/	/cdf/s2/auerbach/benbhelbdNEW.11/
bhelbh	/cdf/s9/auerbach/cafTest/bhelbh/	/cdf/s2/auerbach/benbhelbhNEW.11/
bhelbi	/cdf/s9/auerbach/cafTest/bhelbi/	/cdf/s2/auerbach/benbhelbiNEW.11/
bhelbi, bhelbj	/cdf/s13/auerbach/cafTest/bhelij/	/cdf/s2/auerbach/benbhelbij.11/
bhelbj	/cdf/s9/auerbach/cafTest/bhelbj/	/cdf/s2/auerbach/benbhelbjNEW.11/
bhelbk	/cdf/s9/auerbach/cafTest/bhelbk/	/cdf/s2/auerbach/benbhelbkNEW.11/
bhelbm	/cdf/s9/auerbach/cafTest/bhelbm/	/cdf/s2/auerbach/benbhelbmh.11/ /cdf/s2/auerbach/benbhelbmlow.11/
bhelbm	/cdf/s9/auerbach/cafTest/newbhelbm/	/cdf/s2/auerbach/newelbm.11/
bhmubd	/cdf/s13/auerbach/cafTest/bhmubd/	/cdf/s2/auerbach/benbhmubdNEW.13/
bhmubh	/cdf/s9/auerbach/cafTest/bhmubh/	/cdf/s2/auerbach/benbhmubhNEW.13/
bhmubi	/cdf/s9/auerbach/cafTest/bhmubi/	/cdf/s2/auerbach/benbhmubiNEW.13/
bhmubi, bhmubj	/cdf/s13/auerbach/cafTest/bhmuij/	/cdf/s2/auerbach/benbhmubij.13/
bhmubj	/cdf/s9/auerbach/cafTest/bhmubj/	/cdf/s2/auerbach/benbhmubjNEW.13/
bhmubk	/cdf/s9/auerbach/cafTest/bhmubk/	/cdf/s2/auerbach/benbhmubkNEW.13/
bhmubm	/cdf/s9/auerbach/cafTest/bhmubm/	/cdf/s2/auerbach/benbhmubmNEW.13/
bhmubm	/cdf/s9/auerbach/cafTest/newbhmubm/	/cdf/s2/auerbach/newmubm.11/

Table A.6: Location of the TTGntuples processed on the CDF CAF, and then transferred to the University of Chicago machines.

Dataset	Number of Zs	Number of W's	Number of lg$\not{E}_T$	Number of llg
TTG (μ)	$31.43 \pm .13$	$474.78 \pm .52$	$.72 \pm .020$	$.19 \pm .010$
UC (μ)	$31.43 \pm .13$	$474.95 \pm .52$	$.74 \pm .020$	$.19 \pm .010$
TTG (e)	$31.91 \pm .13$	$700.59 \pm .63$	$.83 \pm .022$	$.27 \pm .012$
UC (e)	$31.86 \pm .13$	$695.52 \pm .63$	$.83 \pm .022$	$.27 \pm .012$

Table A.7: TTG vs UC ntuple comparison for Muon events. The luminosity was found using the good run list v17 with em mu and silicon. We see decent agreement between TTG and UC ntuples with a disagreement of 2%. Using the good run list and the SAM lumi script we find the luminosity to be 1.78 pb^{-1}

ttbar Z, the other also includes gluon fusion. Both papers are for the LHC, but maybe the authors can comment on the k-factor for the Tevatron."

Frank Petriello on k-factor:

"We have not yet completed the ttbar+photon calculation; we hope to have it done by the end of the summer. It is difficult to give an estimate. Since you're only interested in a 15% estimate I will give you one, but let me first give the caveats.

Besides the obvious (different phase space and pdfs), the matrix elements are quite different for ttbar+Z and ttbar+photon. ttZ has contributions from the axial couplings of the Z, which are enhanced by $(mt/mz)^2$*. Furthermore, the ttH calculation of Dawson, Reina, Wackeroth showed a large difference when going from LHC −> Tevatron. The K-factor went from 1.2-1.4 (depending on scale choice) to 0.75-0.95. This was due to various phase space effects, pimarily Coulomb corrections. Because of this it is not clear that going from a massive Z to a massless photon is a*

CDF Run II Preliminary, 4.8fb^{-1}			
Lepton + Photon + $\not\!\!E_T$ + b Events, Isolated Leptons			
Double Counting Source	$e\gamma b\not\!\!E_T$	$\mu\gamma b\not\!\!E_T$	$(e+\mu)\gamma b\not\!\!E_T$
Jets Faking Photons and Electrons Faking Photons	0.0085	0	0.00850
Jets Faking Photons and Mistags	2.51	1.92	4.430
Jets Faking Photons and QCD	1	1	2.000
Electrons Faking Photons and QCD	0	0	0
Mistags and QCD	0.52	0.022	0.542
Mistags and electrons faking photons	0.16	0.054	0.214
Total amount of Double Counting	4.20	2.99	7.190

Table A.8: This table shows the predicted amount of double counting between two data- driven backgrounds for the $\ell\gamma\not\!\!E_T b$ signal

CDF Run II Preliminary, 4.8fb^{-1}			
$t\bar{t}\gamma$, Isolated Leptons			
Double Counting Source	$e\gamma b\not\!\!E_T$	$\mu\gamma b\not\!\!E_T$	$(e+\mu)\gamma b\not\!\!E_T$
Jets Faking Photons and Electrons faking Photons	0.0085	0	0.00850
Jets Faking Photons and Mistags	1.24	1.23	2.470
Jets Faking Photons and QCD	0	0	0
Electrons Faking Photons and QCD	0	0	0
Mistags and QCD	0	0	0
Mistags and electrons faking photons	0.043	0.027	0.070
Total amount of Double Counting	1.29	1.26	2.550

Table A.9: This table shows the predicted amount of double counting between two data- driven backgrounds for the $t\bar{t}\gamma$ signal

minor change.

I would estimate the K-factor using the following argument. In the soft photon limit, the corrections will be the same as for ttbar production, and lead to a K-factor of 1.3-1.4. For hard gluon emission, the negative Coulomb corrections would give a K-factor less than 1. The result should be some average of these two effects. Some effect like seen in ttH when going from LHC $->$ Tevatron should be present for ttZ and tt+photon (to a lesser extent).

For lack of anything else right now, I would assign k=1.10+-0.15; larger than the ttH Tevatron result because of the phase-space, but not quite as large as just ttbar. This shouldn't be viewed as much more than a guess. It is important to note that this k-factor is using NLO α_s and pdfs for the NLO cross section and LO α_s and pdfs for LO, as ttH and ttbar are defined that way. I would definitely follow Uli's suggestion below to study the effect of various K-factors on your analysis."

So for k-factor we will take $k_{factor} = 1.10 \pm 0.15$

NLO cross-section from MadGraph with the k-factor applied is cross-section is $0.080 \pm 0.011 pb^{-1}$

For double-checking the cross-section we also contacted Uli Baur:

"ahhh! Now I know why you couldn't get agreement. Madgraph also includes contributions from single top production whereas we only include doubly resonant diagrams (ie. diagrams which

CDF Run II Preliminary, 4.8fb^{-1}			
$t\bar{t}\gamma$, Isolated Leptons, Tighter Chi2 Cut on Photons			
Double Counting Source	$e\gamma b\not{E}_T$	$\mu\gamma b\not{E}_T$	$(e+\mu)\gamma b\not{E}_T$
Jets Faking Photons and Electrons faking Photons	0.0085	0	0.00850
Jets Faking Photons and Mistags	1.05	1.23	2.280
Jets Faking Photons and QCD	0	0	0
Electrons Faking Photons and QCD	0	0	0
Mistags and QCD	0	0	0
Mistags and electrons faking photons	0.043	0.027	0.070
Total amount of Double Counting	1.10	1.26	2.360

Table A.10: This table shows the predicted amount of double counting between two data- driven backgrounds for the $t\bar{t}\gamma$ signal

have both a top and an antitop).

Uli Baur also advised us to use madgraph only:

"I think you should use the madgraph calculation as it appears to be more complete. And a k-factor.

B Selection Criteria

Some of the ID variables are different from those used in the UCNtuple. For instance, for the UCNtuple we've selected the primary event vertex as follows:

- **Step 1**:
  The vertex chosen is the class 12 vertex with the smallest pull under 5 sigma to the highest pt tight lepton.
- **Step 2**:
  If no vertices are close or there are no class 12 vertices, then the lepton z0 is used.
- **Step 3**:
  If there is no high pt tight lepton, it uses the highest sumpt class 12 vertex.
- **Step 4**:
  If there are no class 12 vertices, then the highest sumpt primary vertex is used.
- **Step 5**:
  If there are no vertices, then the origin is used.

For the Stntuple (and therefore, for the derived TTGNtuple, see Appendix **??**), we've selected the primary event vertex as follows:

- **Step 1**:
  The primary vertex is defined by the vertex which has the highest sum of objects' pt coming from it.

Choice of primary vertex affects E_T of photons and jets.
Other minor changes in object ID are described in the subsections below.

B.1 Lepton Selection: Muons

We require at least one 'tight central muon', photon, b-jet and $\not\!\!E_T$ in a event for it to be classified as a $\mu\gamma\not\!\!E_T b$ event. We also search for additional muons using a definition of 'loose central muon'. We describe these two sets of cuts below.

B.1.1 Muon Cuts

These cuts are identical to the standard cuts [17], [18]. with the exception that we have not applied the impact parameter cut and we don't use cuts on fiducial distance (x-fid, z-fid).

Classification of muons according to [17], [18] is as follows:

- **Tight** (CMUP or CMX)
- **Loose**
  - **Loose CMUP or CMX** (with looser COT cuts)
  - **Stubless** (without stub, or with either CMU or CMP, or BMU etc. stub only, i.e. not CMUP or CMX muons)

Variable	Tight	Loose	Stubless
Track P_t	$> 20\ GeV$	$> 12\ GeV$	$> 12\ GeV$
Track quality cuts	3x3SLx5 hits	3x2SLx5 hits	3x3SLx5 hits
Track $\|z0\|$	$< 60\ cm$	$< 60\ cm$	$< 60\ cm$
Calorimeter Energy (Em)	$<$ 2 + sliding	$<$ 2 + sliding	$<$ 2 + sliding
Calorimeter Energy (Had)	$<$ 6 + sliding	$<$ 6 + sliding	$<$ 6 + sliding
Fractional Calorimeter Isolation E_T	< 0.1	< 0.1	< 0.1
Cosmic	False	False	False
Chi2/(N of COT hits-5)	-	-	$<$ 3
Cal.Energy (EM+Had)	-	-	$>$ 0.1
CMUP muons cuts(*)	yes	yes	no
CMX muons cuts(**)	yes	yes	no

Table B.1: Muon Identification and Isolation Cuts for 533.
(*)CMUP muons cuts: $|\Delta X(CMU)| < 3\ cm$, $|\Delta X(CMP)| < 5\ cm$
No muons from CMP bluebeam section for run<154449
(**)CMX muons cuts: $|\Delta X(CMX)| < 6\ cm$, rho(COT) $>$ 140 cm (COT exit radius)
No muons from the CMX keystone or miniskirt before October 2004 shutdown (run 186598)

Tight central muons are identified by extrapolating tracks in the COT through the calorimeters, and the extrapolation is required to match to a stub either in both the CMU and CMP muon detectors (a 'CMUP' muon), or in the CMX system(a 'CMX' muon). Tight central muons are required to have a track-stub matching distance less than 3 cm for CMU, less than 5 cm for CMP, and less than 6 cm for CMX.

"Region is OK" cut requires:

- for CMUP muons
  - No muons from CMP bluebeam section for run<154449
- for CMX muons
  - rho(COT) $>$ 140 cm (COT exit radius)
  - No muons from the CMX keystone ot miniskirt before October 2004 shutdown (run 186598)

This is what we have for "Region is OK" column in event printouts:

```
BlueBeam : (fRegion   & 0x2) == true
MiniSkirt: (fRegion   & 0x1) == true
KeyStone : (fRegion   & 0x4) == true
All other:  fRegion = 0
```

We use both CMUP and CMX muons as tight muons.

To differentiate between CMU CMP, and CMX muons we check for stubs in the respective subdetectors. The stubs each have at least 3 hits in the detector.

The impact parameter calculation uses the default muon track rather than the parent COT track, and in the Top Group selection a tighter cut is applied if the track does in fact contain silicon hits.

The muon tracks used in the initial selection for this analysis are beam-constrained COT-only, as is done by the muon group in their efficiency studies [17]. For default muon tracks that contain silicon we link backwards to the COT-only parent track and use that track for all subsequent analysis. Muon tracks that have silicon hits and those that do not form two distinctly different samples, with different backgrounds [19], and different resolutions; this technique, while losing valuable information from the silicon at this stage, puts all prompt COT tracks on the same footing (however tracks with impact parameter, such as those from very high-momentum tau decay, would be much better treated using the silicon).

For tracks that are COT-only beam-constrained tracks, we also apply a curvature correction [20] for the track p_T in data before applying kinematic selection criteria and calculating additional kinematic variables. The form of the curvature correction is shown in Equation B.1 where Q is a charge of track(+1 for positive charge and -1 for tracks negative charge):

$$\begin{aligned}
&c = c + 0.00020 * sin(\phi + 3.4) \\
&c = c + 0.00022 * sin(3 * \phi + 0.9) \\
&c = c - (0.000026 + 0.000072 * cot(\theta) - 0.00024 * cot(\theta) * cot(\theta)) \\
&c = c - 0.0002 * cot(\theta) * sin(\phi - 0.9) - 0.0002 * cot(\theta) * cot(\theta) * sin(\phi - 4.1) \\
&p_T = Q/c
\end{aligned} \tag{B.1}$$

All central muons are required to have $|z_0| < 60\ cm$ so that the collision is well-contained within the CDF detector. In order to be well-measured, the muon track is required to have minimum of 3 axial and 3 stereo superlayers with at least 5 hits in each superlayer.

High energy muons are typically isolated 'minimum-ionizing' particles that have limited calorimeter energy. A muon traversing the central electromagnetic calorimeter(CEM) deposits an average energy of $\sim$ 0.3 GeV. Therefore we require muon candidates to deposit less than 2 GeV total in the CEM towers (we take into account two towers in the CEM) the muon track intersects. Similarly, muons transversing the central hadronic calorimeter(CHA) deposit an average energy of $\sim$ 2 GeV; we consequently require muon candidates to deposit a total energy less than $\sim$ 6 GeV, also increasing with muon momentum, in the CHA towers intersected by the track extrapolation. To take into account the (slow) growth of energy loss with momentum, for very high energy muons ($p > 100\ GeV$) we require the measured CEM energy to be less than $2.0 + 0.0115 * (p - 100)\ GeV$ and CHA energy to be less than $6.0 + 0.028 * (p - 100)\ GeV$.

To suppress hadrons and decay muons created from hadrons in jets we require the total transverse energy deposited in the calorimeters in a cone of R=0.4 around the muon track direction(known as the fractional calorimeter isolation E_T) to be less than 0.1 of the muon track pt.

The COT cosmic finder by itself is essentially fully efficient. Therefore, to suppress cosmic rays we use the COT-based cosmic rejection from the CosmicFinderModule [21, 22] and reject events which it tagged as Cosmic Ray muons.

B.1.2 Loose Central CMUP and CMX Muons

While each $\mu\gamma \not\!\!E_T b$ event has to contain at least one tight CMUP or CMX muon, both $\mu\gamma \not\!\!E_T b$ and $e\gamma \not\!\!E_T b$ events are searched for additional high-P_T muons that could come from the decays of heavy particles. There are two types of secondary muons we accept: 'Loose' CMUP and CMX muons, described here, and stubless muons (see Section B.1.3).

Loose muons are muon objects with either CMUP or CMX stubs, but with looser COT cuts than the tight CMUP or CMX muons (see Table B.1). We require 3 axial and 2 stereo COT super layers with at least 5 hits each for loose CMUP and CMX muons.

B.1.3 Loose Central Muons: Stubless

The cuts for the Stubless muons are looser than the tight cuts, and in particular do not require a stub in the muon chambers.

There are three types of 'Stubless' muons:

- CMU muons (muon track matches the CMU stub only);
- CMP muons (muon track matches a stub in the CMP only;
- CMIO muons (muon track doesn't match any stub).

We require at least some energy in the calorimeter towers that the muon extrapolates to, Calorimeter Energy (Em+Had) > 0.1 GeV, and a good fit to the COT track, χ^2/(N of COT hits-5)<3 [19, 17]. These two cuts are used to reject charged kaon decays in flight in which a low-momentum kaon ($\sim$ 5 GeV, typically) decays inside the COT with the kaon and decay-muon tracks forming a 'seagull' pattern which is reconstructed as a single high-momentum track.

The pattern-finding algorithm often removes a complete stereo layer in order to get a good fit, and so these tracks are badly mis-reconstructed in polar angle. Consequently they are often recorded leaving zero energy in the extrapolated traversed calorimeter towers [19].

B.2 Lepton Selection: Electrons

We require at least one 'tight central electron' in an event for it to be classified as an $e\gamma\not\!\!E_{\mathrm{T}}b$ event. We also search for additional 'loose' electrons in the CEM and PEM. We describe the tight central and loose central and plug cuts below.

B.2.1 Electron Selection Criteria

The selection cuts are standard [23] with the exception that the fiducial requirement and the conversion cut are not applied (same as in Ref. [24]).

B.2.2 Tight Central Electrons

The selection criteria for tight central electrons are described below.

Electrons are identified in the CEM by matching high momentum tracks to high-energy CEM clusters. The electron track is the highest momentum track which intersects one of two towers in the CEM cluster. The electron tracks that we use in this analysis are beam-constrained COT-only. We apply the same corrections to the electron tracks as we do to the muon tracks. The selection cuts are standard [23] with the exception that the fiducial requirement and the conversion cut are not applied.

An electron candidate is required to have tracking momentum (P) which exceeds half of its calorimeter energy (E). The electron track is required to have a minimum of 3 axial and 2 stereo SL segments containing at least 5 hits each. In order that the momentum resolution doesn't make for inefficiencies for very high-energy electrons, for $E_T > 100\ GeV$ the E/P cut is not applied (leaving only the the $\mathrm{P_T} > 25$ GeV cut as the requirement on the track). The electrons are required to

Variable	Tight	Tight100	Loose
E_T	> 20 GeV	> 100 GeV	> 12 GeV
Track P_T	> 10 GeV	> 25 GeV	> 10 GeV
Track $\|z0\|$	< 60 cm	< 60 cm	< 60 cm
Had/Em	$< 0.055 + 0.00045\times$E	$< 0.055 + 0.00045\times$E	$< 0.055 + 0.00045\times$E
E/P	< 2.0	-	-
Lshr	< 0.2	-	-
Chi2 Strips	< 10	-	-
ΔX	-3.0 cm $< Q_{trk} \times \Delta X <$ 1.5 cm	$\|\Delta X\| < 3.0$ cm	-
$\|\Delta Z\|$	< 3.0 cm	< 5.0 cm	-
Fractional Calorimeter Isolation E_T	< 0.1	< 0.1	< 0.1
Track quality cuts	3 Ax, 2 St SL x 5 hits	3 Ax, 2 St SL x 5 hits	3 Ax, 2 St SL x 5 hits

Table B.2: Central Electron Identification and Isolation Cuts for Offline Version 5.3.3.

Variable	Tight	Phoenix Tight
E_T	> 15 GeV	> 15 GeV
Had/Em	< 0.05	< 0.05
Fractional Calorimeter Isolation E_T	< 0.1	< 0.1
Chi2 Strips	< 10	< 10
Delta R	< 3.0 cm	< 3.0 cm
PES 5by9 U and V	> 0.65	> 0.65
PEM $\|\eta\|$	$2.0 < \|\eta\| < 1.2$	$2.0 < \|\eta\| < 1.2$
PhxMatch	-	TRUE
Number of Silicon Hits	-	≥ 3
|Z(Phoenix)|	-	< 60 cm

Table B.3: Plug Electron Identification and Isolation Cuts for Offline Version 5.3.3. We are using the "Phoenix Tight" selection [1], [2].

have the track extrapolate to the beam line within $|Z_0| < 60$ cm so that CDF detector contains the collision well.

The position of the track extrapolated to the CES radius must satisfy the following requirements: it must fall within charge-signed CES shower position of the cluster in the r-phi view -3.0 cm $< Q_{trk} \times \Delta X <$ 1.5 cm and it must fall within 3 cm of the CES shower position in the Z-direction(ΔZ).

The CEM shower characteristics should be consistent with that of a single charged particle. We require the ratio of the total energy of the CHA towers located behind the CEM towers in the electron cluster to that of the electron itself to be less than than 0.055+0.00045×E GeV. A comparison of the lateral shower sharing with neighboring towers in the CEM cluster with test-beam data is parameterized by a dimensionless quantity, L_{shr}, which must have a value less than 0.2.

We require the χ^2 for the profile of energy deposited in the CES strips compared to that expected from test beam data to be less than 10. No χ^2 cut is made on the profile in the CES wires as bremsstrahlung will separate from the electron in the $r\phi$ view.

As an additional isolation requirement, the total transverse energy deposited in the calorimeter in a cone R=0.4 around the electron track, must be less than 0.1 of the E_T of the electron. The isolation is corrected via the standard algorithm [25], for leakage, but not the number of vertices.

We don't apply 'Conversion Flag' and 'Fiducial' cuts to select electrons.

The acceptance gain by removing the fiduciality requirement is approximately 14% [24].

B.2.3 Loose Central Electrons

While each $e\gamma \not{E}_T b$ event has to contain at least one tight electron, both $e\gamma \not{E}_T b$ and $\mu\gamma \not{E}_T b$ events are searched for additional high-P_T electrons that could come from the decays of heavy particles. The cuts for these additional electrons are looser than the tight cuts, and in particular do not require any of the CES variables, i.e. no track-cluster match in ΔX or ΔZ and no cut on strip χ^2, and also no cut on Lshr.

B.2.4 Plug Electrons

Additional isolated electrons in the plug calorimeter with $E_T > 15$ GeV are identified for measured PEM rapidities of $1.2 < |\eta| < 2.0$. Each entry corresponds to a Cdf Plug Em Object. We require minimal leakage or activity in the hadron calorimeter, Had/Em < 0.05, a fractional isolation (isolation energy over the electron energy) less than 0.1, and the shower shape to satisfy the the PEM 3x3 χ^2 and PES 5by9 5-strip to 9 strip ratio cuts.

These cuts are similar to standard cuts [23] with the exception that we use PEM-based η instead of PES-based η (Pes2dEta).

We apply face corrections to the PEM energy of the plug electron candidate, add the PPR energy and scale resulting number by 1.0315, as shown in Equation B.2.

$$E_{plug\ electron} = (E_{pem}^{cor} + E_{ppr}) \times 1.0315 \quad \text{(B.2)}$$

B.3 Photon Selection

The photon selection criteria are identical for photons in both the muon and electron samples; the photon cuts are described below.

B.3.1 Photon Selection Criteria

A photon candidate is required to have corrected transverse energy greater than 10 GeV. For photons or electrons the CES shower position is determined by the energy-weighted centroid of the highest energy clusters of those strips and wires in the CES which correspond to the seed tower. The direction of the photon is determined by the line connecting the primary event vertex to the shower position in the CES.

To ensure that events are well-measured the shower position of the photon is required to fall within the fiducial region of the CES so that the shower is fully contained in the active region.

Photon candidates are required to have characteristics consistent with those of a neutral electromagnetically-interacting particle. No COT track with $P_T > 1$ GeV may point at the photon cluster. One track with $P_T < 1$ GeV may point at the cluster.

The variable 'IsoE_T^{corr}' is the Run I cone 0.4 isolation energy with the Run I correction to isolation energy due to phi-crack leakage [25]. The tracking isolation variable 'TrackIso' is the sum of the P_T of tracks in a cone 0.4 surrounding the photon, measured in GeV.

Variable	Cut
E_T^{corr}	> 10 GeV
Had/Em	< 0.125 or $< 0.055 + 0.00045 \times E^{corr}$
χ^2 (Strips+Wires)/2.0	< 20
N Tracks	≤ 1
Track P_T	$< 1{+}0.005 \times E_T^{corr}$ GeV
Cone 0.4 IsoE_T^{corr}	$< 2.0{+}0.02 \times (E_T^{corr} - 20)$ GeV
Cone 0.4 TrackIso	$< 2.0{+}0.005 \times E_T^{corr}$ GeV
2nd CES Cluster (Strip and Wire)	$< 2.4{+}0.01 \times E_T^{corr}$ GeV
Fiducial	Ces$\|X\| < 21$ cm, 9 cm $<$ Ces $\|Z\| < 230$ cm

Table B.4: Photon Identification and Isolation Cuts for Version 5.3.3 of the Offline Code.

B.4 B-Tag Identification

The b-jet selection criteria are identical for b-jets in both the muon and electron samples and described below. We are using the b-tagging collection "PROD@SecVtxModule-JetClu-cone0.4-loose"

The jets used in this analysis are reconstructed from calorimeter tower using a cone algorithm with a radius R $\geq$ 0.4, for which E_T of each tower is calculated with respect to the z coordinate of the event. The calorimeter towers belonging to any electron candidate are not used by the jet clustering algorithm. The energy of the jet is corrected for the pseudo-rapidity dependence of the calorimeter response, the calorimeter time dependence, and extra E_T from any multiple interactions.

We require that the event contains at least one jet with Level 5 corrected $E_T > 15 GeV$ and detector rapidity $|\eta| < 2$ is identified as a b quark candidate through the presence of displaced vertex within the jet arising from the decay of a long-lived bottom hadron (b-tag). We use loose SECVTX tagging method for b-tag identification.

For $t\bar{t}\gamma$ category in addition to $\mathrm{H_T} > 200\ GeV$ we require total number of jets in the event to be > 2.

B.5 Calculating the Missing Transverse Energy and H_T

B.5.1 Calculating the $\not\!\!E_{\mathrm{T}}$

Missing E_T ($\not\!\!E_{\mathrm{T}}$) is the signature of neutrinos, or possible new non-interacting particles such as the gravitino or LSP. It also can come from mis-measurement of the true E_T of objects, or from backgrounds such as cosmic rays or beam halo.

Missing transverse energy $\not\!\!E_{\mathrm{T}}$ is calculated from the calorimeter tower energies in the region $|\eta| < 3.6$. Corrections are then made to the $\not\!\!E_{\mathrm{T}}$ for non-uniform calorimeter response [26] for jets with uncorrected $\mathrm{E_T} > 15\ GeV$ and $\eta < 2.0$, and for muons with $\mathrm{P_T} > 12\ GeV$:

- Muons: correct for $E_T - P_T$, where E_T is transverse energy deposited in electromagnetic and hadron calorimeters, and P_T is a transverse momentum of a muon track. We correct $\not\!\!E_{\mathrm{T}}$ for all muons with $\mathrm{E_T} > 20$ GeV.
- Jets: correct for $E_T - E_T^{corr}$, where E_T is a transverse energy of an uncorrected jet, and E_T^{corr} is a transverse energy of a jet, corrected for non-uniform calorimeter response. We correct for jets with $\mathrm{E_T^{corr}} > 15$ GeV.

When identifying jets we check that jet object does not have any of the objects identified in the current analysis close to it (within $\Delta R < 0.5$).

For the $\ell\gamma\not{E}_{\mathrm{T}}b$ and $t\bar{t}\gamma$ analysis we set the cut on $\not{E}_{\mathrm{T}}$ to be $\not{E}_{\mathrm{T}} > 20$ GeV.

B.5.2 Calculating the H_T

H_T is a sum of E_T's and P_T's of all objects in the event (leptons, photons, $\not{E}_{\mathrm{T}}$, jets). To calculate H_T we use Tight and Loose Central Electrons(Table B.2), Tight Phoenix Electrons (Table B.3), Tight and Loose CMUP and CMX muons, Stubless muons(Table B.1), $\not{E}_{\mathrm{T}}$, and jets in the event with $|\eta| < 2$ and $E_T^{corr} > 15$.

For the $t\bar{t}\gamma$ analysis we set the cut on $\mathrm{H_T}$ to be $\mathrm{H_T} > 200$ GeV.

C Systematic Uncertainties

In this section we summarize preliminary estimates of the systematic uncertainties on the SM predicted rates. The errors are categorised as experimental(Section C.1, theoretical(Section C.2) and luminosity(Section C.3).

The contributing effects for the SM predictions we have considered are:

- Error is on the total theoretical prediction, including the NLO uncertainties (different for different samples, see Section C.2).
- Luminosity: 6%
- Trigger Efficiencies: 2% for muons and 1% for electrons for lepton triggers only.
- |z_vert| < 60: 1%
- Muon ID Efficiencies: 2%
- Electron ID Efficiencies: 1%
- Photons ID Efficiencies: 4%
- B-tagging ID Efficiencies: 5%

The systematic uncertainties on the backgrounds are included in the background estimates, discussed in Section **??** and Section 4.

The total systematic uncertainty for the SM predictions for the $t\bar{t}\gamma$ samples is 18%. The total systematic uncertainty is 13% for $W\gamma + HF$ and WW samples.

C.1 Experimental Systematic Uncertainties

The sources of experimental systematic errors [27, 28, 29] are summarized in Table C.1.

C.2 Theoretical Systematic Uncertainties

Limitations in the theoretical precision of the calculation, result in an uncertainty on the cross-section prediction. The effect of the errors on the cross-section for $W\gamma$ and $Z\gamma$ samples is studied in [27, 28, 29].

Based on these studies we estimate systematic error to be 10% for $W\gamma$+HF and WW samples. For the $t\bar{t}\gamma$ samples we also add k-factor (14% uncertainty, see Section A.4) systematic error in addition to the factorization scale error (2% as estimated for $W\gamma$ and $Z\gamma$ samples) and PDF uncertainty (6% as estimated for $W\gamma$ and $Z\gamma$ samples). The resulting theoretical systematic uncertainty for $t\bar{t}\gamma$ samples is 15%.

C.3 Luminosity Systematic Uncertainties

A total systematic uncertainty of 6% is quoted for all luminosity measurements. This includes a 4.4% contribution from the acceptance and operation of the luminosity monitor and 4.0% from the theoretical uncertainty on the calculation of the total $p\bar{p}$ cross-section [30].

Source	%	Central	CMUP	CMX
Jet Fake	≈50-80	x	x	x
Z_0 cut eff	1.0	x	x	x
photon cut eff	2.0	x	x	x
energy scale (γ)	3.0	x	x	x
conversion rate uncertainty	1.5	x	x	x
momentum scale (μ)	2.0		x	x
acceptance (e)	1.0	x		
acceptance (μ)	2.0		x	x
central e ID	1.0	x		
central e trigger	1.0	x		
energy scale (e)	1.0	x		
cosmic	0.01		x	x
Cot track reconstruction	0.4	x	x	x
B-tagging	5.0	x	x	x
CMUP ID	0.7		x	
CMUP reconstruction	0.6		x	
CMUP trigger	0.7		x	
CMX ID	0.8			x
CMX reconstruction	0.3			x
CMX trigger	0.6			x

Table C.1: Systematic error summary for $\ell\gamma$. 'x' means that channel needs to take into account its systematic uncertainty. Jet Fake systematic error is discussed in Section **??**

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