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Search for Anomalous Production of Photon + Jets + $\not\!\!E_T$

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Abstract

Many new physics models predict mechanisms that could produce a γ and jets signature. We search in the γ + jets and γ + jets + $\not\!\!E_T$ channels, independent of any model, for new physics using 2 fb^{-1} of CDF Run II data collected at the Fermilab Tevatron from $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. A variety of techniques are applied to estimate the standard model expectation and non-collision backgrounds. We examine several kinematic distributions including $\not\!\!E_T$, ΣE_T, and invariant masses for discrepancies with the standard model.

1 Introduction

We present the preliminary findings of a γ + jets + $\not\!\!E_T$ signature-based search using only one tenth of the data (events with event number divisible by 10). We begin by describing the datasets used in this analysis. Then we explain the signal selection, sources of backgrounds, and the methods used to estimate the remaining backgrounds in the signal sample. We have made predictions and estimations of all backgrounds from the full dataset; therefore, all backgrounds are scaled down by a factor of 10 to match the signal sample.

2 Datasets

We use the high-p_T photon datasets `cph10d`, `cph10h`, `cph10i`, and `cph10j` which were collected at CDF during the run periods 1–13 (run range 190851 to 246231) with triggers PHOTON_ISO_25, PHOTON_50, and PHOTON_70. These triggers are high-p_T photon triggers which suit our resonance search. Good run list `goodrun_v19_pho_00` from the Photon Group is used to estimate the luminosity. After the good run selection the total luminosity is 2043 pb^{-1} and this is excludes the first 400 pb^{-1} of data (run range >=138425 & <190851) that has no EM timing information.

We use Monte Carlo data samples for validation, cross checks, and to predict the shape of the electroweak background and fake $\not\!\!E_T$ from real γ events.

1. Inclusive γ dataset `jqcdfh` Pythia Monte Carlo sample generated with a minimum photon p_T of 22 GeV/c by the CDF QCD Group.

The following inclusive run dependent PYTHIA Monte Carlo datasets from the CDF EWK group are also used.

2. $Z \to e^+e^-$: zewk6d, zewkad, zewkcd, zewkdd, zewked, zewkee, zewkeh, and zewkej
3. $Z \to \mu^+\mu^-$: zewk6m, zewk9m, zewkbm, zewkcm, zewkdm, zewkem, zewkfm, and zewkgm
4. $Z \to \tau^+\tau^-$: zewk8t and zewkat
5. $W \to e\nu$: wewkfe, wewkge, wewkhe, wewkie, wewkeh, and wewkej
6. $W \to \mu\nu$: wewk7m, wewk8m, wewk9m, wewk1m, wewkbm, and wewkgm
7. $W \to \tau\nu$: wewk9t and wewkat

3 Event Selection

We select the γ + jets signal according to selection criteria listed below. The γ is removed from the jet list and all other EM objects that are not identified are treated as jets. We have minimal restrictions for jets and require one or more jets with corrected transverse energy, $E_T > 15$ GeV. All jets are corrected up to level 6 (underlying event corrections) using standard jet energy corrections [3] before cutting on E_T. They can be within $|\eta^{detector}| < 3.0$ whereas the photon is required to be central.

1. The run number must be in the good run list.
2. The event should pass the PHOTON_25_ISO, PHOTON_50 or PHOTON_70 trigger.
3. There should be at least one good class 12 vertex (except in the case of beam halo template).
4. The z-coordinate of the highest-p_T vertex should be within the well-instrumented region, i.e. $|z| < 60$ cm (except in the case of beam halo template).
5. Require one reconstructed photon with $E_T > 30$ GeV that passes tight photon ID cuts (see Table 4).
6. Photon should be in-time (-4.8 ns $< t <$ $+4.8$ ns)
7. Not a phoenix photon[1]
8. Not beam halo
9. $\geq$1 jets, $E_T > 15$ GeV

[1]These photons are mostly from bremsstrahlung radiation produced by high-energy electrons deflected in the electric field of the atoms as they traverse through detector material. If the electron loses most of its energy in this process, it would not make it to the calorimeter and we would not have enough hits in the tracking chambers to reconstruct the track. Without a track, the radiated photon will look like a photon that origniated from the primary hard scattering process. The phoenix tracking algorithm starts from the calorimeter seed and tracks backward looking at traces of the electron track. It uses COT hits, silicon hits, the primary vertex information, and its complicated matrix elements to identify these track segments. If a track is found it is called a phoenix track and hence the name phoenix photon.

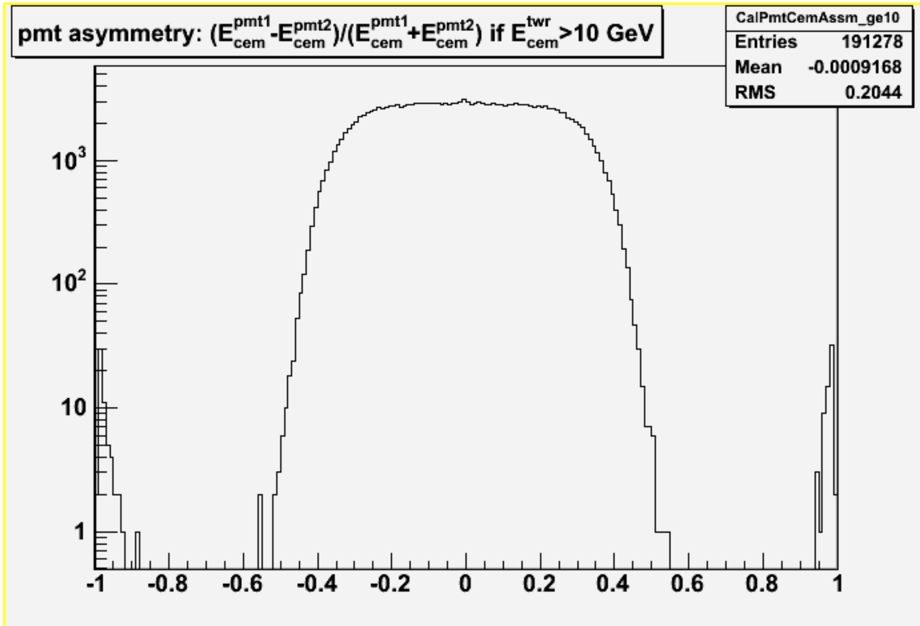

Figure 1: PMT Asymmetry. The clumps at the extremes indicate PMT spikes. These events lead to fake $\not\!\!E_T$ and hence they are thrown out.

4 Backgrounds

We can divide our backgrounds into two categories: standard model backgrounds and non-collision backgrounds. Compared to the standard model backgrounds, non-collision backgrounds are hard to deal with as they occupy the high end of the $\not\!\!E_T$ distribution where we intend to look for new physics.

4.1 PMT Spike Removal

This is a non-collision background due to the misbehavior of the electronics used to read out the calorimeter. They would fire at random (called a PMT spike) mimicking a real signal. In the central region each calorimeter tower is equipped with two phototubes. If one of the phototubes has a reading but there is nothing from the other this probably means it is a PMT spike. We can remove these events by calculating the asymmetry of the two phototubes as defined as below.

$$\text{PMT Asymmetry} = \frac{|E^{PMT1} - E^{PMT2}|}{|E^{PMT1} + E^{PMT2}|} \tag{1}$$

where E is the energy (signal) read out from the PMT. By cutting at –0.6 and +0.6 we reject 100% of these fake events.

4.2 γ^{halo} + jets

This is a non-collision background that overlaps with a real collision. The protons and anti-protons that are not coalesced, upon hitting the beam pipe, create a miniature shower. Only the muons (μ)

survive to make it through the beam pipe. These muons (dubbed the beam halo) travel parallel to the beam and interact with the calorimeter, depositing energy to create an EM cluster that passes photon-ID cuts, making it looks like a real photon. Beam halo tend to occupy phi wedges 0 and 23 of the CDF detector.

To identify and reject the beam halo background we use EM timing and topological cuts (see Table 6). We estimate the rejection power of the beam halo cuts by selecting events with no reconstructed vertices, which should primarily be from beam halo and cosmic ray backgrounds. Then we look for an in-time (-4.8 ns $< t <$ $+4.8$ ns) photon passing tight photon ID cuts and plot the phi-wedge distribution of the photon before and after the halo ID cuts are applied. We count events in phi-wedges 0 and 23 and subtract off the flat component (cosmic) estimated from the phi-wedges 1 through 22.

$$\text{Rejection Power} = \frac{\text{Events in wedges } 0,23 \text{ after cuts} - \text{Average of wedges 1–22 after cuts}}{\text{Events in wedges } 0,23 \text{ before cuts} - \text{Average of wedges 1–22 before cuts}} = 94.8\% \quad (2)$$

The Beam Halo template is made with the following selection criteria. This is normalized to the expecteted number of events (see Table 2).

1. The run number must be in the good run list.
2. The event should pass the PHOTON_25_ISO, PHOTON_50 or PHOTON_70 trigger.
3. A reconstructed photon with $E_T > 30$ GeV that passes tight photon ID cuts (Table 4).
4. Photon should be in-time (-4.8 ns $< t <$ $+4.8$ ns)
5. Photon should be in phi-wedge 0 or 23
6. Pass beam halo id cuts (Table 6)

4.3 γ^{cosmic} + jets

This is a case when a cosmic ray (extraterrestrial high energy muon passing through the earth) interacts with the calorimeter. It is a constant background that is independent of the time of the collision. So we use EM timing to make a template for γ^{cosmic} + jets. We drop the first 400 pb^{-1} of data because it does not have EM timing information to reject this background efficiently.

To estimate the amount of background remaining in the sample, we count events in the time window between $+30$ ns $< t <$ $+90$ ns and then we extrapolate to the signal window:

$$\text{Cosmics left in the sample} = \frac{\text{Number of events in window (30–90 ns)}}{90 - 30} \times (4.8 \times 2) \quad (3)$$

The template for this background is made with the following selection rules and it is normalized to the expected number of events (see Table 2).

1. The run number must be in the good run list.
2. The event should pass the PHOTON_25_ISO, PHOTON_50 or PHOTON_70 trigger.

3. There should be at least one good class 12 vertex (except in the case of beam halo template).
4. The z-coordinate of the highest-p_T vertex should be within the well-instrumented region, i.e. $|z| < 60$ cm (except in the case of beam halo template).
5. Require one reconstructed photon with $E_T > 30$ GeV that passes tight photon ID cuts (see Table 4).
6. Photon should be between $+30$ ns $< t < +90$ ns
7. $\geq$1 jets

4.4 $\gamma^{e\rightarrow\gamma}$ + jets

This is a standard model background where an electron fakes a photon because the associated track is not reconstructed. Most of these electrons come from $W^{\pm} \rightarrow e^{\pm} + \nu$ decay. Less significant contributions come from Z, di-boson, and τ decays. We use phoenix rejection of photons to remove $\gamma^{e\rightarrow\gamma}$ + jets events from the sample. Phoenix rejection is about 60% efficient in rejecting electrons with energies $E_T > 30$ GeV.

To predict the shapes of the remaining $\gamma^{e\rightarrow\gamma}$ + jets we use an Electroweak Monte Carlo data sample. We identify γ + jets events according to the criteria listed below and normalize each background by the luminosity.

1. The run number must be in the good run list.
2. There should be at least one good class 12 vertex (except in the case of beam halo template).
3. The z-coordinate of the highest-p_T vertex should be within the well-instrumented region, i.e. $|z| < 60$ cm (except in the case of beam halo template).
4. Require one reconstructed photon with $E_T > 30$ GeV that passes tight photon ID cuts (see Table 4).
5. Reject if phoenix photon
6. $\geq$1 jets

4.5 QCD Background

This accounts for all the QCD processes that can produce or mimic the γ + jets signal, primarily jets faking γ's. We use γ sideband to predict this background. The following selection criteria are used to predict the shape of this background.

1. The run number must be in the good run list.
2. The event should pass the PHOTON_25_ISO, PHOTON_50 or PHOTON_70 trigger.
3. There should be at least one good class 12 vertex (except in the case of beam halo template).
4. The z-coordinate of the highest-p_T vertex should be within the well-instrumented region, i.e. $|z| < 60$ cm (except in the case of beam halo template).

5. Require one reconstructed photon with $E_T > 30$ GeV that passes loose photon ID cuts (Table 3) and fails tight photon ID cuts (Table 4).

6. Photon should be in-time, -4.8 ns $< t < +4.8$ ns

7. Not a phoenix photon

8. Not beam halo

9. $\geq$1 jets, $E_T > 15$ GeV

From the CES/CPR weight, the fake photon fraction for photons with $E_T > 30$ GeV is determined to be $0.319 \pm 0.001(\text{stat}) \pm 0.068(\text{syst})$. We normalize this background as follows.

$$\text{Normalization} = \frac{\text{Total Number of Signal Events} \times 0.319}{\text{Total Number of Sideband Events}} \tag{4}$$

To fill up the rest, we used γ Monte Carlo to get the shape of the real photons in the sideband sample. It is normalized in such a way that sum of the sideband fraction and the pure photon fraction to be equal to 100%.

4.6 Jet Energy Resolution

This is due physical limitations in the detector in measuring the energy deposited by the objects. To predict the shape of this background in the $\not\!\!E_T$ distribution, we use the $\not\!\!E_T$ resolution model.

5 Systematics Uncertainties

5.1 γ^{cosmic} + jets

Since this background is very small we take the statistical uncertainty of each bin as the systematic error for that bin.

5.2 $\gamma^{e\to\gamma}$ + jets

We take the uncertainty in the Luminosity measurement of the electroweak Monte Carlo data as the systematic uncertainty of the electroweak backgrounds, which 10%.

5.3 γ^{halo} + jets

Systematic uncertainty for the halos taken to be 50% of the bin content as this background is insignificant.

5.4 QCD Background

We use 100% of the photon sideband sample to predict the shape for some histograms and for some we use a mixture with the photon Monte Carlo.

Where we use 100% of the sideband sample, we apply the following prescription to estimate the systematics.

1. Notice that there are four selection ID variables common to both loose photon ID cuts (Table 3) and tight photon ID cuts (Table 4), (Had/Em, Isolation Energy, Track p_T and Track Isolation)

2. Tighten up the loose ID cuts to match the tight photon ID cuts one at a time.

3. Run the sideband sample through the new set of cuts.

4. Normalize the number of events passed back to the sideband sample obtained with the standard set of ID cuts.

5. Divide the variable (histogram) by the corresponding standard sideband variable (histogram).

6. Plot all four histograms obtained by varying the four cuts on the same histogram for each kinematic variable.

7. Take the maximum variation in each bin to be the systematic uncertainty for that bin.

In the case where we use the mixture of sideband and the photon Monte Carlo, we vary the mixture to get a reasonable systematic uncertainty.

6 Summary of Background Estimates

Background	**Expected for ≥1Jet**	**Expected for ≥2 Jets**
SM Photon	2.6M	650K
QCD	1M	280K
EWK	459	111
Cosmic	110	7
Beam Halo	9	≤1
PMT Spikes	0	0

Table 1: Summary of background estimates. All these are estimated for the full dataset.

7 Acknowledgement

We like to thank Shin-Shan Eiko Yu providing us with the fake photon fraction and for all the advice. Also we want to thank Max Goncharov answering various questions and providing the run dependent EM time corrections. Finally I would like to thank my wife, Vajira, my daughter, Amaya, and my family for their patience and support.

References

[1] CDF–8220, R. Culbertson *et al.*, "Probability of an Electron Faking an Isolated Prompt Photon in CEM", May 30, 2006.

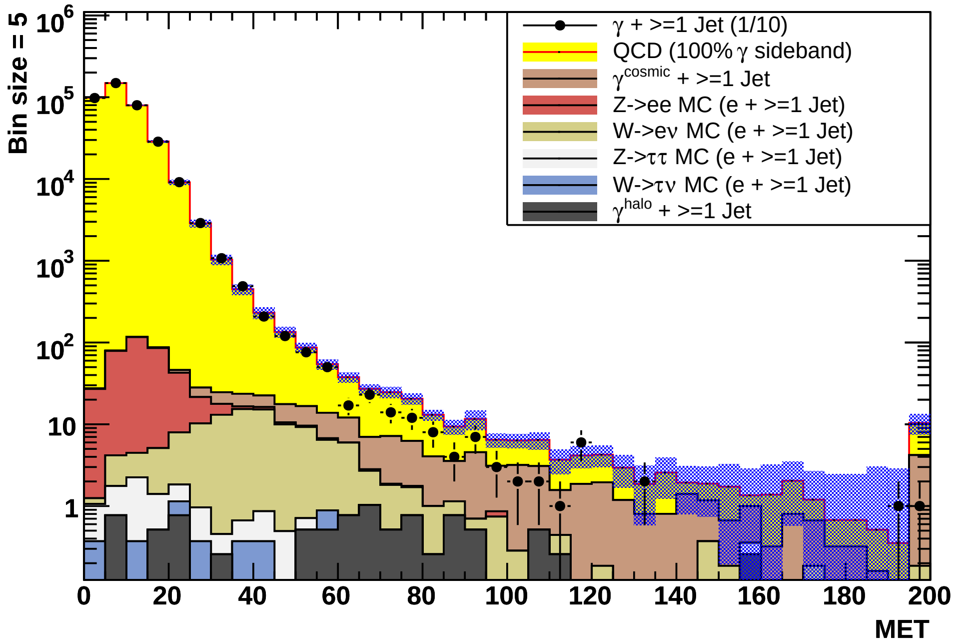

Figure 2: $\not\!\!E_T$ for the $\gamma+\geq 1$ jet

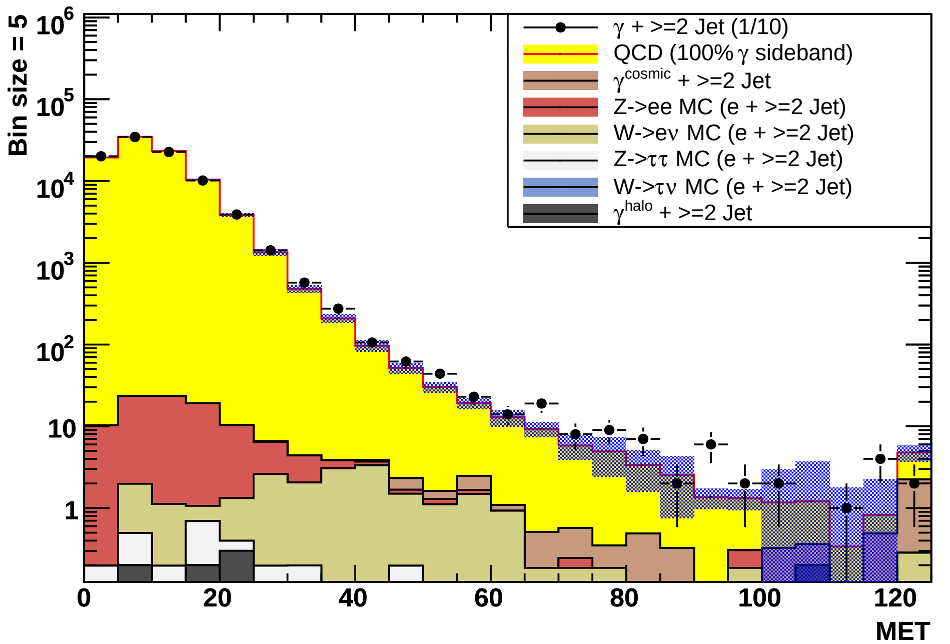

Figure 3: $\not\!\!E_T$ for $\gamma+\geq 2$ jets

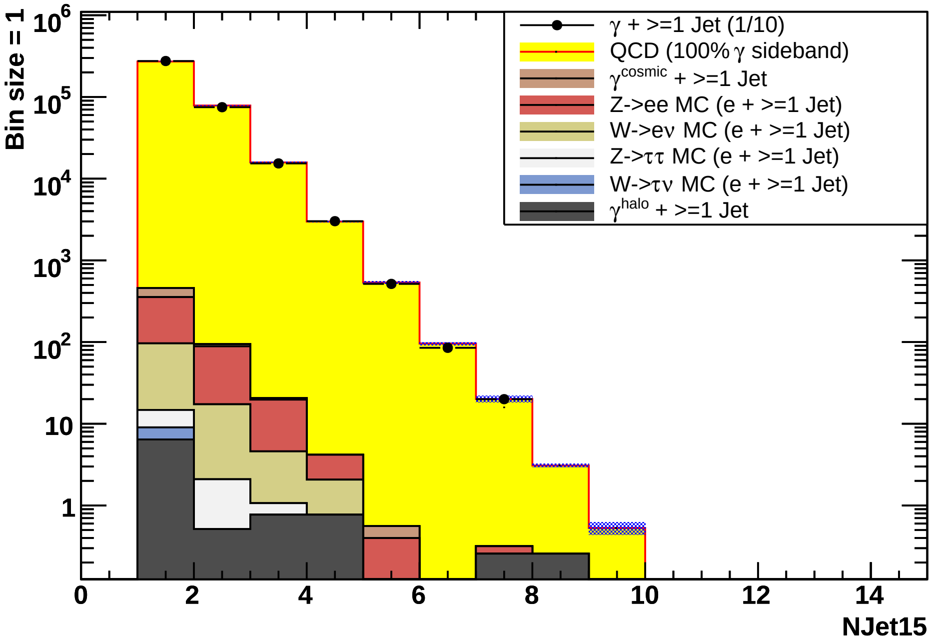

Figure 4: Jet Multiplicity for $\gamma+\geq 1$ jet

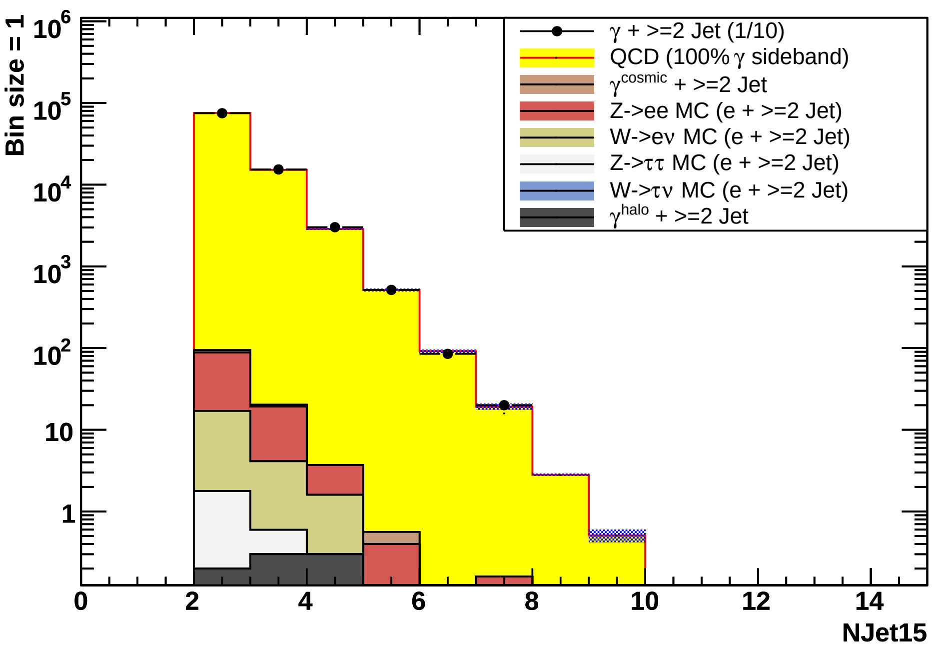

Figure 5: Jet Multiplicity for $\gamma+\geq 2$ jets

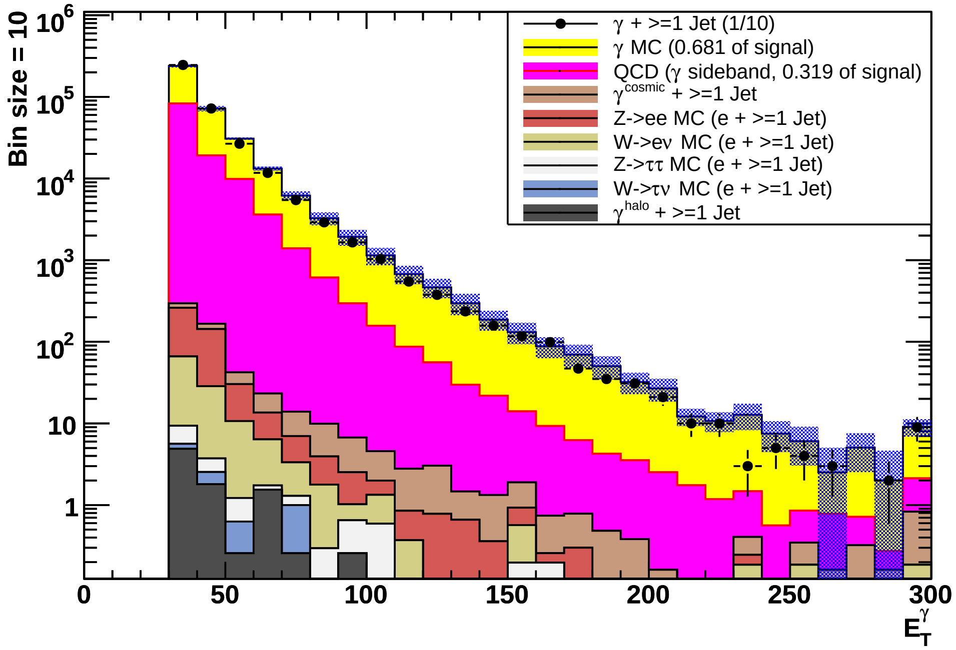

Figure 6: Photon E_T for $\gamma+\geq 1$ jet

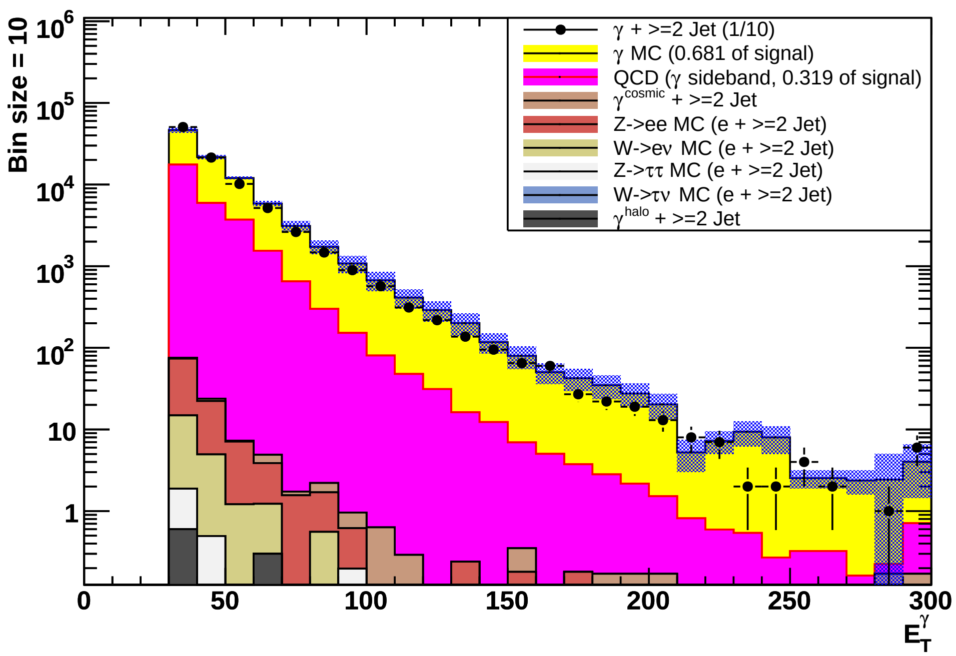

Figure 7: Photon E_T for $\gamma+\geq 2$ jets

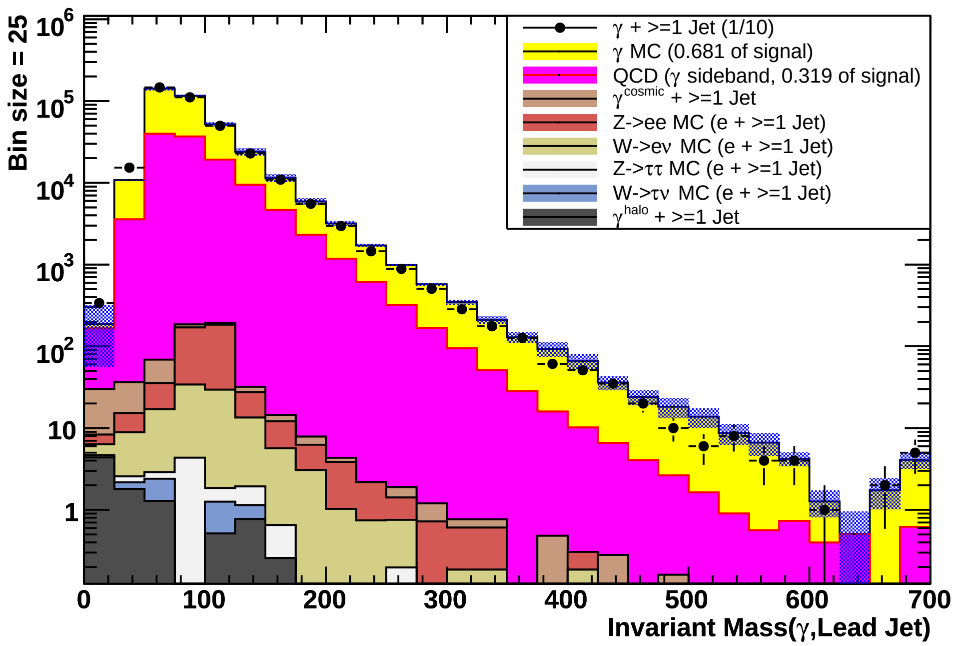

Figure 8: Invariant Mass of the photon and the lead jet for $\gamma+\geq 1$ jet.

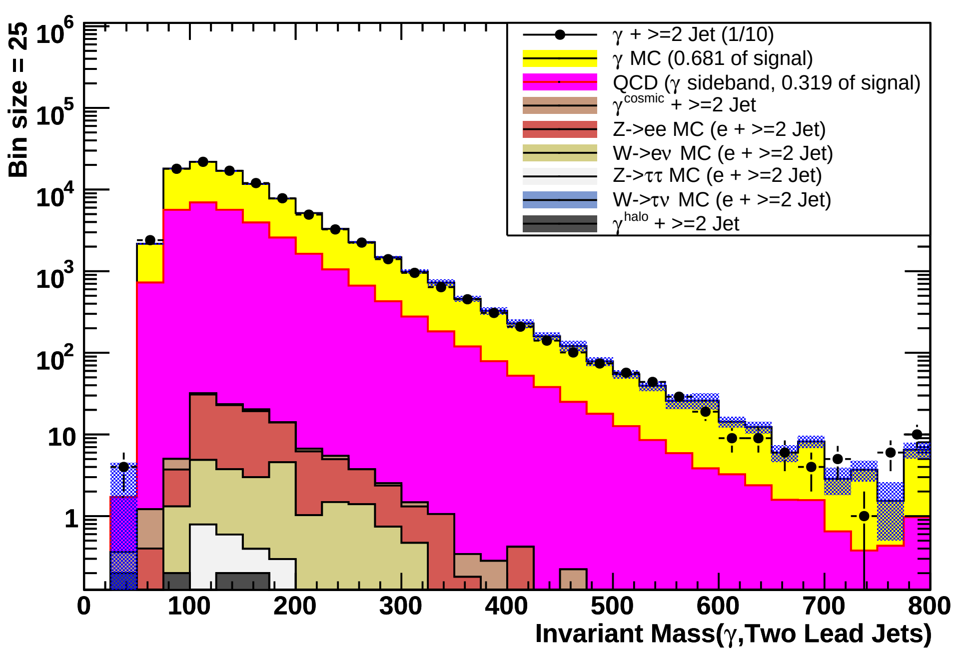

Figure 9: Invariant Mass of the photon and the two lead jets for $\gamma+\geq 2$ jets.

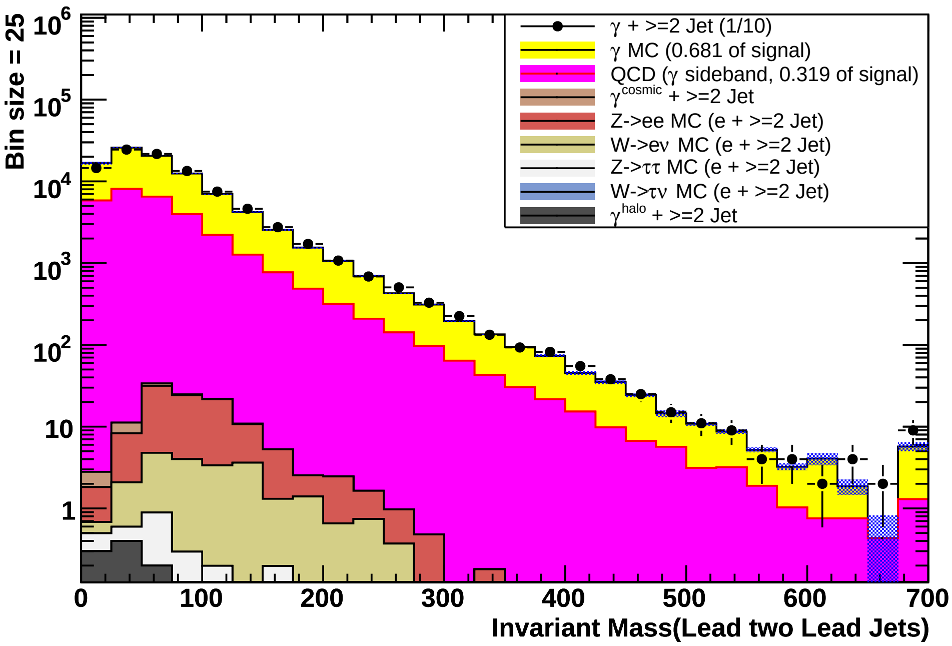

Figure 10: Invariant Mass of the two lead jets for $\gamma+\geq 2$ jets.

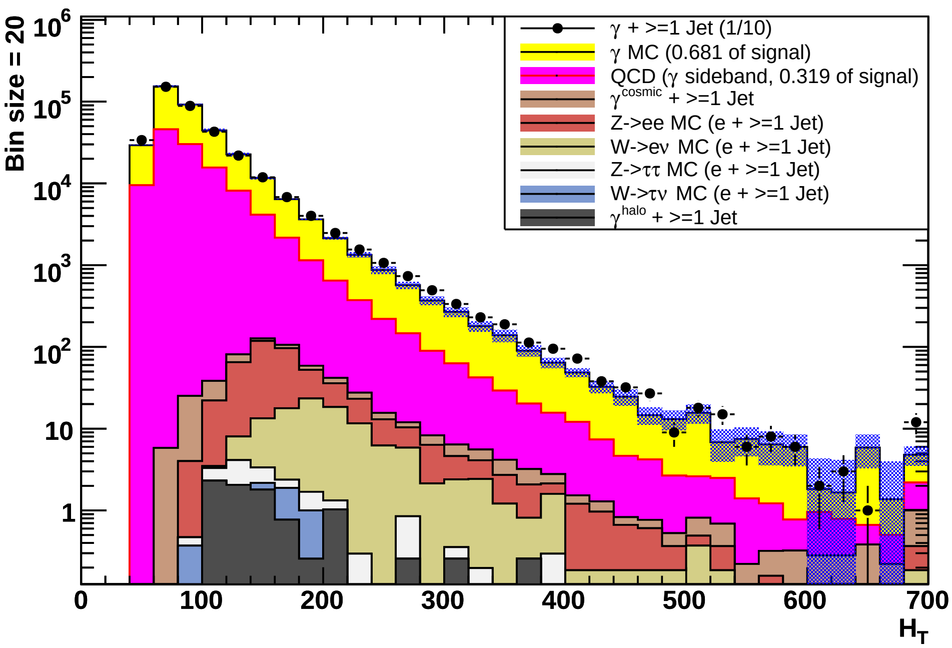

Figure 11: H_T for $\gamma+\geq 1$ jet.

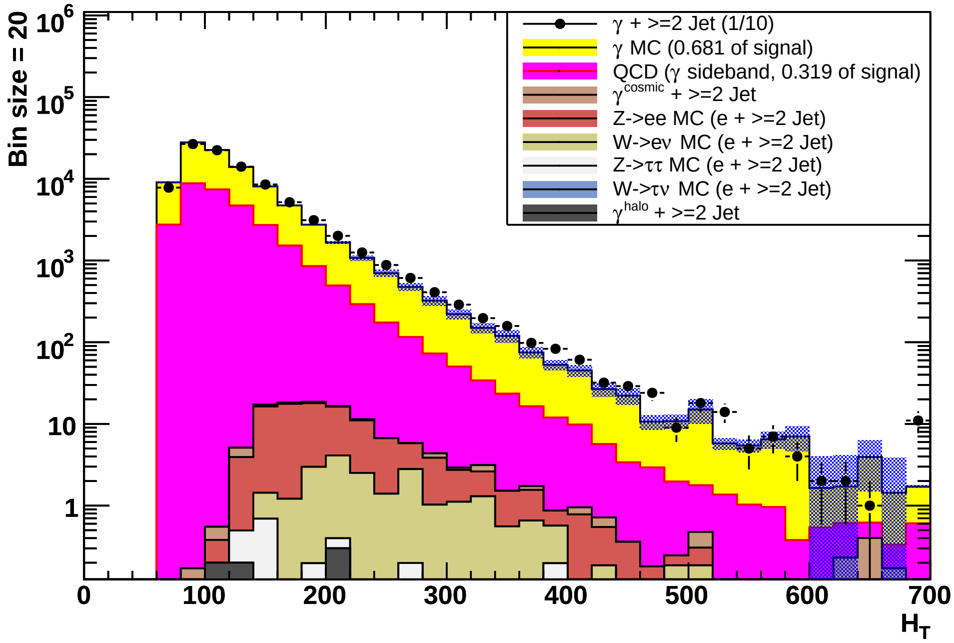

Figure 12: H_T for $\gamma+\geq 2$ jets.

[2] CDF–9224, S. Hewamanage *et al.*, "Validation of Photon Sample by Estimating $W \rightarrow e + \nu$ and $Z \rightarrow e^+e^-$ Cross Sections", March, 2008.

[3] CDF Jet Energy and Resolution Group, "http://www-cdf.fnal.gov/internal/physics/top/jets/corrections.html"

Background	**Template Events ≥1Jet**	**Template Events ≥2 Jets**
SM Photon	231K	49K
QCD	2.1M	554K
$Z \to e^+e^-$	5786	1481
$Z \to \mu^+\mu^-$	0	0
$Z \to \tau^+\tau^-$	78	20
$W \to e + \nu$	548	108
$W \to \mu + \nu$	0	0
$W \to \tau + \nu$	7	0
Cosmic	685	43
Beam Halo	35	10

Table 2: Summary of Number of Events in Background Templates.

Variable	**Cut value**
detector	central
E_T^{corr}	> 30 GeV
CES X and Z fiducial	$\lvert X_{CES}\rvert \leq 21$ cm 9 cm $\leq \lvert Z_{CES}\rvert \leq 230$ cm
Had/Em	≤ 0.125
$E_T^{Iso(corr)}$in cone 0.4	$\leq 0.15 \times E_T^{corr}$ if E_T^{corr} <20 GeV ≤ 3.0 if E_T^{corr} >20 GeV
Track p_T	$< 0.25 \times E_T^{corr}$
Track Iso(0.4)	< 5.0

Table 3: Loose Photon ID cuts.

Variable	**Cut value**
detector	central
E_T^{corr}	> 30 GeV
CES X and Z fiducial	$\lvert X_{CES}\rvert \leq 21$ cm 9 cm $\leq \lvert Z_{CES}\rvert \leq 230$ cm
Had/Em	$\leq 0.125 \mid\mid \leq 0.055 + 0.00045 \times E^{corr}$
$E_T^{Iso(corr)}$in cone 0.4	$\leq 0.1 \times E_T^{corr}$ if $E_T^{corr} < 20$ GeV $\leq 2.0 + 0.02 \times (E_T^{corr} - 20)$ if $E_T^{corr} > 20$ GeV
average CES χ^2 (Strips+Wires)/2	≤ 20
N tracks in cluster (N3D)	≤ 1
Track p_T	$< 1 + 0.005 \times E_T^{corr}$
Track Iso(0.4)	$< 2.0 + 0.005 \times E_T^{corr}$
2$^{\text{nd}}$ CES cluster $E \times sin(theta)$ (both wire and strip E individually)	$\leq 0.14 \times E_T^{corr}$ if $E_T^{corr} < 18$ GeV $\leq 2.4 + 0.01 \times E_T^{corr}$ if $E_T^{corr} \geq 18$ GeV

Table 4: Tight Photon ID cuts.

Variable	Cut value
detector	central
corrected E_T	> 30 GeV
CES fiducility	$\lvert X_{CES}\rvert \leq 21$ cm 9 cm $\leq \lvert Z_{CES}\rvert \leq 230$ cm
average CES χ^2	≤ 20
Had/Em	$\leq 0.055 + 0.00045 \times E$
$E_T^{Iso(corr)}$in cone 0.4	$\leq 0.1 \times E_T$ if $E_T < 20$ GeV $\leq 2.0 + 0.02 \times (E_T - 20)$ if $E_T \geq 20$ GeV
N3D tracks in cluster	$= 1, 2$
E/p of 1st track	$0.8 \leq E/p \leq 1.2$ if $p_T < 50$ GeV no cut if $p_T \geq 50$ GeV
2nd track p_T if N3D = 2	$\leq 1.0 + 0.005 \times E_T$
TrkIso(0.4) - p_T(1st track)	$\leq 2.0 + 0.005 \times E_T$
E_T of 2nd CES cluster (wire and strip)	$\leq 0.14 \times E_T$ if $E_T < 18$ GeV $\leq 2.4 + 0.01 \times E_T$ if $E_T \geq 18$ GeV
$\lvert\Delta z\rvert = z_{vtx} - z_{trk}$	≤ 3 cm

Table 5: Photon-like electron ID cuts.

Variable	Cut value
seedWedge	> 8
Nhad	> 3

Table 6: Beam Halo ID cuts. *seedWedge* is defined as number of EM towers (E_T >0.1GeV) in the same wedge as γ and *Nhad* as the number of plug HAD towers (E_T >0.1GeV) in same wedge as γ.