



Measurement of  $W\gamma$  and  $Z\gamma$  Production in  $p\bar{p}$  Collisions at  
 $\sqrt{s} = 1.96$  TeV

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The Standard Model predictions for  $W\gamma$  and  $Z\gamma$  production are tested using an integrated luminosity of  $200 \text{ pb}^{-1}$  of  $p\bar{p}$  collision data collected at the Collider Detector at Fermilab. The cross sections are measured selecting leptonic decays of the  $W$  and  $Z$  bosons, and photons with transverse energy  $E_T > 7 \text{ GeV}$  that are well separated from leptons. The cross sections for both  $W\gamma$  and  $Z\gamma$  production are found to agree with the Standard Model predictions. The kinematic distributions are also in good agreement with those predicted by the Standard Model.

The study of the characteristics of  $W\gamma$  and  $Z\gamma$  production is an important test of the Standard Model (SM) description of gauge boson interactions and is sensitive to physics beyond the SM. The  $W\gamma$  and  $Z\gamma$  cross sections are directly sensitive to the trilinear gauge couplings which are uniquely predicted by the non-Abelian gauge group of the SM electroweak sector  $SU(2)_L \times U(1)_Y$ .  $W\gamma$  production can be used to study the  $WW\gamma$  vertex and  $Z\gamma$  production can be used to constrain the  $ZZ\gamma$  and  $Z\gamma\gamma$  vertices which vanish in the SM [1–3]. Physics beyond the SM (e.g. compositeness models or excited  $W$  or  $Z$  bosons) could alter the cross sections and the production kinematics.  $W\gamma$  and  $Z\gamma$  production are also important background contributions to searches for new physics, e.g. in Gauge Mediated Supersymmetry Breaking models [4].

This report presents measurements of  $W\gamma$  and  $Z\gamma$  production from  $p\bar{p}$  collisions at  $\sqrt{s}=1.96$  TeV at the Tevatron accelerator using data obtained with the upgraded Collider Detector at Fermilab (CDF). Throughout this letter the notation “ $Z$ ” is used to specify  $Z/\gamma^*$  production via the Drell-Yan process. The data are taken at higher center of mass energy and constitute a larger data sample by at least a factor of two than previous measurements [5–7]. They were collected between March 2002 and September 2003, and correspond to an integrated luminosity of about  $200 \text{ pb}^{-1}$ .  $W$  and  $Z$  bosons are selected in their electron and muon decay modes. Additionally, a photon with transverse energy above 7 GeV is selected. The production properties of the  $W\gamma$  and  $Z\gamma$  events are compared to the SM predictions.

The CDF detector is described in detail elsewhere [8]. Transverse momenta of charged particles  $(p_T)^1$  are measured by an eight-layer silicon strip detector [9] and a 96-layer drift chamber (COT) [10] inside a 1.4 Tesla magnetic field. The COT provides coverage with high efficiency for  $|\eta| < 1$ . At higher  $|\eta|$  the silicon detector is used for measuring charged particles. Electromagnetic and hadronic calorimeters surround the tracking system. They are segmented in a projective tower geometry and measure energies  $E$  of charged and neutral particles in the central ( $|\eta| < 1.1$ ) and forward ( $1.1 < |\eta| < 3.6$ ) regions. Each calorimeter has an electromagnetic shower profile detector positioned at the shower maximum. Lo-

cated at the inner face of the central calorimeter, the central preradiator chambers use the solenoid coil as a radiator to measure the shower development. These two detectors are used for the photon identification and background determination. The calorimeters are surrounded by muon drift chambers covering  $|\eta| < 1$ . Gas Cherenkov counters [11] measure the average number of  $p\bar{p}$  inelastic collisions per bunch crossing and thereby determine the beam luminosity.

For the  $W$  and  $Z$  boson selection, we follow closely the analysis described in [12]. We require that the event was triggered online. For  $W$  bosons decaying into muons or central electrons and for  $Z$  bosons, the trigger is solely based on the identification of a high transverse momentum lepton [12]. For  $W$ 's decaying to forward electrons, the trigger additionally requires  $\cancel{E}_T > 15$  GeV. Offline a high- $p_T$  lepton ( $l = e, \mu$ ) is required to fulfill tighter selection criteria [12]. Electron candidates are required to have  $E_T > 25$  GeV and  $|\eta| < 2.6$ . In the central region, a COT track with  $p_T > 10$  GeV/ $c$  must be associated with the energy deposition, while in the forward region calorimeter-seeded silicon tracking is used to associate a track with the electromagnetic shower [13]. The electromagnetic shower profile of an electron candidate must be consistent with expectations from test beam data. Muons are selected by requiring a COT track with  $p_T > 20$  GeV/ $c$ , and the associated energy deposition in the calorimeter to be consistent with that expected for a muon [12]. In addition, for at least one muon per event, the track segments in the muon chambers must match the extrapolated position of the muon track and be in the range  $|\eta| < 1.0$ . Both electrons and muons must be isolated from other calorimeter energy depositions [12]. The selected samples correspond to an integrated luminosity of  $202 \text{ pb}^{-1}$  for central electrons,  $168 \text{ pb}^{-1}$  for forward electrons,  $192 \text{ pb}^{-1}$  for muons in the region  $|\eta| < 0.6$ , and  $175 \text{ pb}^{-1}$  for muons within  $0.6 < |\eta| < 1.0$ .

For  $W \rightarrow l\nu$  candidates, we also require  $\cancel{E}_T > 25$  (20) GeV in the electron (muon) channel as evidence for the neutrino. For the  $W \rightarrow \mu\nu$  channel, events with an additional track with  $p_T > 10$  GeV/ $c$  and a calorimeter signal consistent with a muon, are rejected as potential background from  $Z \rightarrow \mu^+\mu^-$ . For the selection of  $Z$  candidates, a second electron is required in the electron channel and a second isolated track consistent with a minimum ionizing particle in the muon channel.

In the  $Z\gamma$  analysis the invariant mass of the dilepton pair,  $M(l^+, l^-)$ , is required to be in the range  $40 < M(l^+, l^-) < 130$  GeV/ $c^2$  to enhance the sensitivity to on-shell  $Z$  boson production. Particularly the lower mass cut on  $M(l^+, l^-)$  reduces the contribution from the  $\gamma^*\gamma$  process. In the  $W\gamma$  analysis the transverse mass,  $M_T(l, \cancel{E}_T)$ , is required to be in the range  $30 < M_T(l, \cancel{E}_T) < 120$  GeV/ $c^2$  to select on-shell  $W$  boson production. The transverse mass is used, since the longitudinal component of the neutrino momentum cannot be

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<sup>1</sup>We use a cylindrical coordinate system about the beampipe in which  $\theta$  is the polar angle,  $\phi$  is the azimuthal angle and  $\eta = -\ln \tan(\theta/2)$ .  $E_T = E \sin \theta$  and  $p_T = p \sin \theta$  where  $E$  is the energy measured by the calorimeter and  $p$  the momentum measured in the tracking system.  $\vec{\cancel{E}}_T = -\sum_i E_T^i \vec{n}_i$  where  $\vec{n}_i$  is a unit vector that points from the interaction vertex to the  $i$ th calorimeter tower in the transverse plane.  $\cancel{E}_T$  is the magnitude of  $\vec{\cancel{E}}_T$ . If muons are identified in the event  $\cancel{E}_T$  is corrected for the muon momenta.

measured:  $M_T(l, \cancel{E}_T) = \sqrt{2p_T \cancel{E}_T (1 - \cos \phi_{l, \cancel{E}_T})}$ , where  $\phi_{l, \cancel{E}_T}$  is the difference in azimuthal angle between the lepton momentum and the missing transverse momentum vector.

After reconstructing a  $W$  or  $Z$  candidate, we select a photon with  $E_T^\gamma > 7$  GeV within  $|\eta_\gamma| < 1.0$  which is isolated from other particles in both the calorimeter and the tracking detectors. The transverse energy deposit around the photon in a cone  $\Delta R = \sqrt{(\eta_i - \eta_\gamma)^2 + (\phi_i - \phi_\gamma)^2} = 0.4$  is required to be less than 10% of the photon transverse energy for  $E_T^\gamma < 20$  GeV and  $\lesssim 2$  GeV for  $E_T^\gamma > 20$  GeV. Here,  $\eta_i$  and  $\phi_i$  denote the location of the energy deposit in the  $i$ th calorimeter tower excluding those associated with the photon candidate. The total sum of the track transverse momenta in a cone of 0.4 around the photon candidate is also required to be less than 2 GeV. To remove electron background we require there to be no track with  $p_T > 1$  GeV/ $c^2$  pointing toward the photon candidate. The photon candidate also must have a shower shape consistent with a single particle and must be separated from the lepton by  $\Delta R_{l, \gamma} = \sqrt{(\eta_l - \eta_\gamma)^2 + (\phi_l - \phi_\gamma)^2} > 0.7$ . This last requirement is placed to suppress the contribution from bremsstrahlung photons. After all selection criteria are applied, 323  $W\gamma$  candidates and 70  $Z\gamma$  candidates are found.

The most important source of background to both the  $Z\gamma$  and  $W\gamma$  analysis is the production of a real  $Z$  or  $W$  boson and a hadron which is misidentified as a photon. The dominant source of this background is from isolated, high energy  $\pi^0$  or  $\eta$  mesons decaying into photons. This background is determined using large event samples triggered on jets at several  $E_T$  thresholds: 20, 50, 70 and 100 GeV. We measure the fraction of jets in the samples which pass all the photon selection requirements. This fraction is then corrected for prompt photon contamination within the jet samples. Two methods were used to estimate this contamination. For  $E_T < 40$  GeV, the estimate of the prompt photon contamination exploits the broader shower shape of  $\pi^0 \rightarrow \gamma\gamma$  showers compared to prompt  $\gamma$  showers in the electromagnetic shower profile detector [14]. For  $E_T > 40$  GeV hits in the central pre-radiator chambers are counted. In this method prompt photons are distinguished from meson decays since the probability of a photon conversion in the magnetic coil is higher for  $\pi^0$ 's than for prompt photons [14]. The resulting fake rate for a jet to pass all photon selection cuts is about 0.3% at  $E_T = 10$  GeV and decreases exponentially to about 0.07% for  $E_T = 25$  GeV.

We obtain the background prediction by applying this fake rate to jets in  $W$  and  $Z$  events. The systematic uncertainty on this background is about 30% at low  $E_T$  and increases with increasing  $E_T$ . The background due to events where neither the leptons nor the photon are genuine is implicitly taken into account in the above es-

timate. We have also investigated the possibility of an additional background from prompt photon production where a jet is misidentified as a lepton, but we found this source to be negligible.

In the  $W\gamma$  analysis an additional background arises from  $Z\gamma$  production where large  $\cancel{E}_T$  is observed due to an undetected lepton. This background is larger in the muon than in the electron channel due to the smaller muon coverage of the CDF detector. Another source of background is  $W\gamma \rightarrow \tau\nu_\tau\gamma \rightarrow l\nu_l\bar{\nu}_\tau\nu_\tau\gamma$  production.<sup>2</sup> These two backgrounds are determined using the Monte Carlo generators described below.  $Z\gamma \rightarrow \tau\tau\gamma$  is found to be a negligible source of background in both analyses.

A summary of the background contributions for the  $W\gamma$  analysis is given in Table I. For the  $Z\gamma$  analysis, the only background is due to jets mis-identified as photons. For  $Z\gamma \rightarrow ee\gamma$ , the estimated background is  $2.8 \pm 0.9$  events, and for  $Z\gamma \rightarrow \mu\mu\gamma$ , it is  $2.1 \pm 0.7$  events.

TABLE I. Background event contributions for the  $W\gamma \rightarrow e\nu\gamma$  and  $W\gamma \rightarrow \mu\nu\gamma$  analyses. The combined statistical and systematic uncertainty on the background prediction is also quoted.

	$W\gamma \rightarrow e\nu\gamma$	$W\gamma \rightarrow \mu\nu\gamma$
W+jet	$59.5 \pm 18.1$	$27.6 \pm 7.5$
$W\gamma \rightarrow \tau\nu\gamma$	$1.5 \pm 0.2$	$2.3 \pm 0.2$
$Z\gamma \rightarrow l^+l^-\gamma$	$6.3 \pm 0.3$	$17.4 \pm 1.0$
Total Background	$67.3 \pm 18.1$	$47.3 \pm 7.6$

The Standard Model signal predictions are determined using leading order  $p\bar{p} \rightarrow W\gamma X \rightarrow l\nu\gamma X$  and  $p\bar{p} \rightarrow Z\gamma X \rightarrow l^+l^-\gamma X$  Monte Carlo generators [2,3]. These generators include initial and final state photon radiation. Initial state QCD radiation and hadronization are included using PYTHIA [15]. Samples were generated for each of the three lepton generations. The parton momentum distribution is modeled with CTEQ5L parton density functions (PDF's) [16].  $\mathcal{O}(\alpha_s)$  QCD corrections [17,18] to the  $W\gamma$  and  $Z\gamma$  production cross sections are calculated using CTEQ5M PDF's [16]. These corrections depend on  $E_T^\gamma$ , and for the measured kinematic region increase the  $W\gamma$  ( $Z\gamma$ ) cross section by 33 – 55% (27 – 32%) for  $E_T^\gamma$  in the range 10 to 55 GeV.

The theoretical cross section prediction for  $p\bar{p} \rightarrow W\gamma X \rightarrow l\nu\gamma X$  production for the kinematic region  $E_T^\gamma > 7$  GeV and  $\Delta R(l, \gamma) > 0.7$  is  $\sigma(W\gamma) \times \mathcal{B}(W \rightarrow l\nu) = 19.3 \pm 1.4$  pb where  $\mathcal{B}(W \rightarrow l\nu)$  is the branching ratio of the  $W$  into a single lepton flavour. For the

<sup>2</sup>This process could also be considered as part of the  $W\gamma$  signal but since it is negligible compared to all the other sources it is treated as background.

same kinematic region and with the invariant mass of the dilepton pair  $M(l^+, l^-) > 40 \text{ GeV}/c^2$ , the cross section for  $p\bar{p} \rightarrow Z\gamma X \rightarrow l^+l^-\gamma X$  production is  $\sigma(Z\gamma) \times \mathcal{B}(Z \rightarrow l^+l^-) = 4.5 \pm 0.3 \text{ pb}$  where  $\mathcal{B}(Z \rightarrow l^+l^-)$  is the branching ratio of the  $Z$  into a single charged lepton flavor. The 7% uncertainty on the cross section due to higher order contributions and uncertainties on the PDF's is evaluated by changing the factorization scale (2%), the renormalization scale (3%) and comparing the predictions made with several PDF's (5%) [19,20].

The observed ( $N_{obs}$ ) and expected numbers of signal ( $N_{sig}$ ) and background ( $N_{bg}$ ) events in the  $W\gamma$  and  $Z\gamma$  analyses are given in Tables II and III, respectively. Both the electron and muon channels are in good agreement with expectations. The systematic uncertainties on these measurements include uncertainties on the event selection efficiency and acceptance. The main contributions come from higher order QCD corrections to the acceptance and the efficiency of the photon selection. The dominant uncertainty on the background is due to jets fragmenting into a leading  $\pi^0$  or  $\eta$  meson decaying into photons. The total systematic error on the cross sections is 9-14% for the  $W\gamma$  and 3% for the  $Z\gamma$  cross sections. An additional uncertainty of 6% arises from the luminosity measurement.

TABLE II. Expected and observed numbers of events for  $W\gamma \rightarrow e\nu\gamma$  and  $W\gamma \rightarrow \mu\nu\gamma$  production. The systematic uncertainty listed for the expected number of events excludes the 7% uncertainty on the theoretical cross section and the 6% uncertainty in luminosity measurement. The measured cross sections  $\sigma \times \mathcal{B}(W \rightarrow l\nu)$  are also listed. The first uncertainty is statistical and the second is systematic. There is a separate error on the luminosity normalization of 1.2 pb for both measurements.

	$W\gamma \rightarrow e\nu\gamma$	$W\gamma \rightarrow \mu\nu\gamma$
$N_{sig}$	$126.8 \pm 5.8$	$95.2 \pm 4.9$
$N_{sig} + N_{bg}$	$194.1 \pm 19.1$	$142.4 \pm 9.5$
$N_{obs}$	195	128
$\sigma \times \mathcal{B}(W \rightarrow l\nu)$ (pb)	$19.4 \pm 2.1 \pm 2.9$	$16.3 \pm 2.3 \pm 1.8$

The cross section  $\sigma(W\gamma) \times \mathcal{B}(W \rightarrow l\nu)$  is measured in the kinematic range  $\Delta R(l, \gamma) > 0.7$  and  $E_T^\gamma > 7 \text{ GeV}$  with  $\sigma \times \mathcal{B} = (N_{obs} - N_{bg}) / (A \times \epsilon \times \int \mathcal{L} dt) = (N_{obs} - N_{bg}) / N_{sig} \times \sigma_{SM}$ . Here,  $\int \mathcal{L} dt$  is the integrated luminosity,  $A$  is the acceptance,  $\epsilon$  is the selection efficiency and  $\sigma_{SM}$  is the SM cross section of the Monte Carlo simulation sample used for estimating the acceptance and number of expected signal events. The resulting cross sections are given in Table II. The measured cross sections are determined for the full  $W$  decay phase space, transverse mass range and photon  $\eta$  range using extrapolations based upon the SM expectation [17,18]. Combining the electron and muon channel, assuming lepton universal-

TABLE III. Expected and observed numbers of events for  $Z\gamma \rightarrow e^+e^-\gamma$  and  $Z\gamma \rightarrow \mu^+\mu^-\gamma$  production. The systematic uncertainty listed for the expected number of events excludes the 7% uncertainty on the theoretical cross section and the 6% uncertainty in luminosity measurement. The measured cross sections  $\sigma \times \mathcal{B}(Z \rightarrow l^+l^-)$  are also listed. The first uncertainty is statistical and the second is systematic. There is a separate error on the luminosity normalization of 0.3 pb for both measurements.

	$Z\gamma \rightarrow ee\gamma$	$Z\gamma \rightarrow \mu\mu\gamma$
$N_{sig}$	$30.9 \pm 1.6$	$33.2 \pm 1.5$
$N_{sig} + N_{bg}$	$33.7 \pm 1.8$	$35.3 \pm 1.6$
$N_{obs}$	35	35
$\sigma \times \mathcal{B}(Z \rightarrow l^+l^-)$ (pb)	$4.7 \pm 0.8 \pm 0.3$	$4.5 \pm 0.8 \pm 0.2$

ity, and taking into account correlations of the systematic uncertainties, yields  $\sigma(W\gamma) \times \mathcal{B}(W \rightarrow l\nu) = 18.1 \pm 3.1 \text{ pb}$ . The theoretical prediction for the cross section is  $\sigma(W\gamma) \times \mathcal{B}(W \rightarrow l\nu) = 19.3 \pm 1.4 \text{ pb}$ .

The cross section  $\sigma(Z\gamma) \times \mathcal{B}(Z \rightarrow l^+l^-)$  is measured in the kinematic range  $\Delta R(l, \gamma) > 0.7$ ,  $E_T^\gamma > 7 \text{ GeV}$  and  $M(l^+, l^-) > 40 \text{ GeV}/c^2$ . We follow the same procedure as for the  $W\gamma$  analysis and obtain the cross section listed in Table III. The measured cross sections are determined for the full  $Z$  decay phase space, dilepton mass range  $M(l^+, l^-) > 40 \text{ GeV}/c^2$  and photon  $\eta$  range using extrapolations based upon the SM expectation [17,18]. The combined electron and muon result is  $\sigma(Z\gamma) \times \mathcal{B}(Z \rightarrow l^+l^-) = 4.6 \pm 0.6 \text{ pb}$ . The theoretical prediction for the cross section is  $\sigma(Z\gamma) \times \mathcal{B}(Z \rightarrow l^+l^-) = 4.5 \pm 0.3 \text{ pb}$ .

In addition to these cross section measurements, we compare the SM predictions for several kinematic variables with the data. The transverse momentum of the photon in  $W\gamma$  and  $Z\gamma$  production is shown in Figure 1. Significant contributions from non-SM processes would result in an excess at high transverse momentum. Figure 2 shows the cluster transverse mass [21],  $M_T(l\gamma, \nu)$ , for  $W\gamma$  events and the invariant mass of the  $(l^+, l^-, \gamma)$  system,  $M(l, l, \gamma)$ , for  $Z\gamma$  events. The data are in good agreement with the SM expectations for both processes. The cluster transverse mass ( $W\gamma$ ) and invariant mass ( $Z\gamma$ ) distributions are sensitive to non-SM processes in the high mass regions.

In summary, we have measured the inclusive production of  $W\gamma$  and  $Z\gamma$  pairs from  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96 \text{ TeV}$  using data from the CDF experiment. The cross sections, measured to a precision of 15%, are compared to electroweak predictions having an estimated uncertainty of 7%. For  $E_T^\gamma$  above 7 GeV and  $\Delta R(l, \gamma) > 0.7$ , the production cross sections, and the photon and  $W/Z$  boson production kinematics, are found to agree well with Standard Model predictions. There is no evidence for any anomalous production of  $W/Z$  bosons and photons

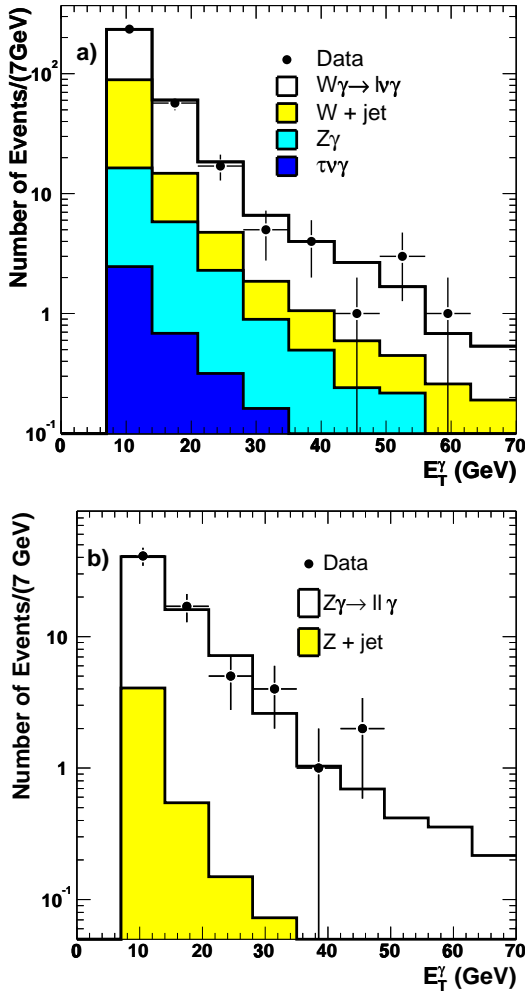


FIG. 1. Photon transverse momentum spectrum,  $E_T^\gamma$ , for a)  $W\gamma$  and b)  $Z\gamma$  candidates selected in the leptonic decay channel. The data are compared with the SM expectations for signal and background with the histograms added cumulatively.

due to contributions from new physics.

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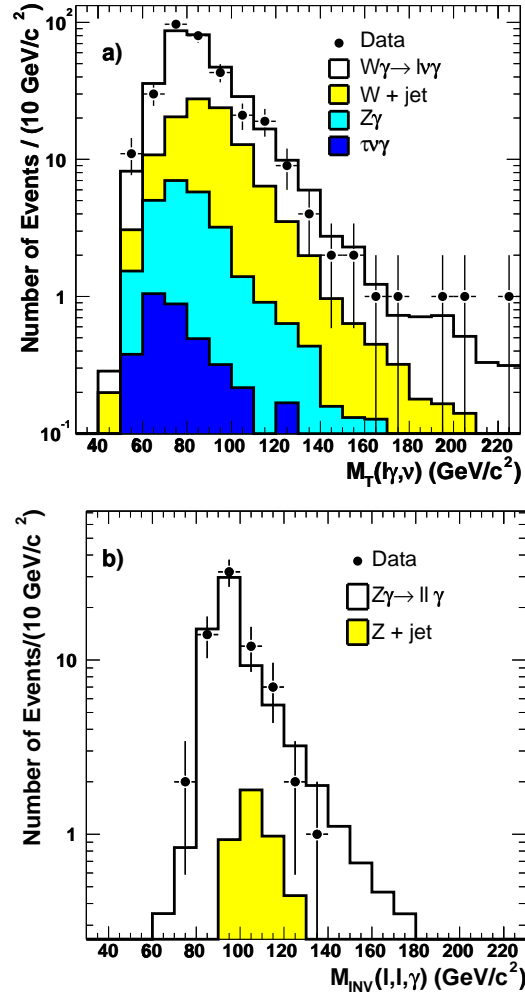


FIG. 2. a) The cluster transverse mass of the lepton-photon-missing  $E_T$  system for  $W\gamma$  candidates, and b) the invariant mass of the lepton-lepton-photon system for  $Z\gamma$  candidates. The data are compared with the SM expectations for signal and background with the histograms added cumulatively.

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