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Electroweak physics: measurement of w gamma and z gamma production in pp-bar collisions at
s**(1/2) = 1.96 tev

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Measurement of $W\gamma$ and $Z\gamma$ Production in $p\overline{p}$ 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 pb^{-1} of $p\overline{p}$ collision data collected at the Collider Detector at Fermilab. The cross sections are measured by selecting leptonic decays of the W and Z bosons, and photons with transverse energy $E_T > 7$ GeV that are well separated from leptons. The production cross sections and kinematic distributions for the $W\gamma$ and $Z\gamma$ data are compared to SM predictions.

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 $p\bar{p} \to l\nu\gamma + X$ and $p\bar{p} \to l^+l^-\gamma + X$ production at $\sqrt{s}$=1.96 TeV at the Tevatron accelerator using data obtained with the upgraded Collider Detector at Fermilab (CDF). In the SM the $l\nu\gamma$ and $l^+l^-\gamma$ final states occur due to $W\gamma \to l\nu\gamma$ and $Z\gamma \to l^+l^-\gamma$ production, as well as via lepton bremsstrahlung: $W \to l\nu \to l\nu\gamma$ and $Z \to l^+l^- \to l^+l^-\gamma$. Throughout this letter the notation "Z" is used to specify Z/γ^* production via the Drell-Yan process. The notations $W\gamma$ and $Z\gamma$ are used to denote the $l\nu\gamma$ and $l^+l^-\gamma$ final states.

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 [5–9]. They were collected between March 2002 and September 2003, and correspond to an integrated luminosity of about 200 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 [10]. Transverse momenta of charged particles (p_T)[1] are measured by an eight-layer silicon strip detector [11] and a 96-layer drift chamber (COT) [12] 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. Located 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 [13] 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 with decays into muons or central electrons, the trigger is solely based on the identification of a high transverse momentum lepton [14]. For W's decaying to forward electrons, the trigger additionally requires $\not{E}_T > 15$ GeV. Offline, a high-p_T lepton ($l = e, \mu$) is required to fulfill tighter selection criteria [14]. 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 [15]. 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 [14]. 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 [14]. The selected samples correspond to an integrated luminosity of 202 pb^{-1} (168 pb^{-1}) for central (forward) electrons and 192 pb^{-1} (175 pb^{-1}) for muons in the region $|\eta| < 0.6$ ($0.6 < |\eta| < 1.0$).

For $W \to l\nu$ candidates, we also require $\not{E}_T > 25$ (20) GeV in the electron (muon) channel as evidence for the neutrino. For the $W \to \mu\nu$ 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 $Z \to \mu^+\mu^-$. 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. In the $W\gamma$ analysis the transverse mass, $M_T(l, \not{E}_T)$, is required to be in the range $30 < M_T(l, \not{E}_T) < 120$ GeV/c^2 to select on-shell W bo-

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[1] We use a cylindrical coordinate system about the beampipe in which θ is the polar angle, ϕ 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. $\vec{\not{E}}_T = -\sum_i E_T^i \vec{n}_i$ where $\vec{n}_i$ is a unit vector that points from the interaction vertex to the ith calorimeter tower in the transverse plane. $\not{E}_T$ is the magnitude of $\vec{\not{E}}_T$. If muons are identified in the event, $\not{E}_T$ is corrected for the muon momenta.

son production. The transverse mass is used since the longitudinal component of the neutrino momentum cannot be measured: $M_T(l, \not{E}_T) = \sqrt{2p^l_T \not{E}_T (1 - \cos\phi_{l,\not{E}_T})}$, where $\phi_{l,\not{E}_T}$ 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 $E^\gamma_T > 7$ 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 $E^\gamma_T < 20$ GeV and less than $2+0.02(E^\gamma_T - 20)$ GeV for $E^\gamma_T > 20$ GeV. Here, η_i and ϕ_i denote the location of the energy deposit in the ith 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/c. To remove electron background we require there to be no track with $p_T > 1$ GeV/c 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 71 $Z\gamma$ 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. 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 $E^\gamma_T < 40$ GeV, the estimate of the prompt photon contamination exploits the broader shower shape of $\pi^0 \to \gamma\gamma$ showers compared to prompt γ showers in the electromagnetic shower profile detector [16]. For $E^\gamma_T > 40$ GeV hits in the central preradiator 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 π^0's than for prompt photons [16]. 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 background due to events where neither the leptons nor the photon are genuine is implicitly taken into account in the above estimate. In the $W\gamma$ analysis an additional background arises from $Z\gamma$ production where large $\not{E}_T$ 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 $\tau\nu_\tau\gamma \to l\nu_l\bar{\nu}_\tau\nu_\tau\gamma$ production. These two backgrounds are determined using the Monte Carlo generators described below. $\tau\tau\gamma$ 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 $ee\gamma$, the estimated background is 2.8 ± 0.9 events, and for $\mu\mu\gamma$, it is 2.1 ± 0.6 events.

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

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

The $p\bar{p} \to l\nu\gamma X$ and $p\bar{p} \to l^+l^-\gamma X$ SM signal predictions are determined using leading order Monte Carlo generators for all three lepton generations. The matrix element generator [2,3] includes initial and final state photon radiation and the $WW\gamma$ vertex diagram. Initial state QCD radiation and hadronization are included using `PYTHIA` [17]. The parton momentum distribution is modeled with CTEQ5L parton density functions (PDF's) [18]. $\mathcal{O}(\alpha_s)$ QCD corrections [19] to the $W\gamma$ and $Z\gamma$ production cross sections are calculated using CTEQ5M PDF's [18]. These corrections increase the $W\gamma$ ($Z\gamma$) cross section by $33 - 55\%$ ($27 - 32\%$) for E^γ_T in the range $10 - 55$ GeV.

The SM cross section for $p\bar{p} \to l\nu\gamma X$ production for the kinematic region $E^\gamma_T > 7$ GeV and $\Delta R(l, \gamma) > 0.7$ is 19.3 ± 1.4 pb for the W-boson decaying into a single lepton flavor. For the same kinematic region and with the invariant mass of the dilepton pair $M(l^+, l^-) > 40$ GeV/c^2, the cross section for $p\bar{p} \to l^+l^-\gamma X$ production is 4.5 ± 0.3 pb for the Z-boson decaying into a lepton pair of a single 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%) [20,21].

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 Table II. Both the electron and muon data 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 the jet fake rate uncertainty. The total systematic uncertainty 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 $e\nu\gamma$ and $\mu\nu\gamma$, $e^+e^-\gamma$ and $\mu^+\mu^-\gamma$ production. The systematic uncertainties listed for the expected number of events excludes the 7% uncertainty on the theoretical cross section and the 6% uncertainty in luminosity measurement. The product of the acceptance and efficiency, $A \times \epsilon$, and the measured cross sections, $\sigma(l\nu\gamma)$ and $\sigma(l^+l^-\gamma)$, 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 the $W\gamma$ and 0.3 pb for the $Z\gamma$ cross section measurements.

	$e\nu\gamma$	$\mu\nu\gamma$
N_{sig}	126.8 ± 5.8	95.2 ± 4.9
$N_{sig} + N_{bg}$	194.1 ± 19.1	142.4 ± 9.5
N_{obs}	195	128
$A \times \epsilon$	3.3%	2.4%
$\sigma(l\nu\gamma)$ (pb)	$19.4 \pm 2.1 \pm 2.9$	$16.3 \pm 2.3 \pm 1.8$
	$e^+e^-\gamma$	$\mu^+\mu^-\gamma$
N_{sig}	31.3 ± 1.6	33.6 ± 1.5
$N_{sig} + N_{bg}$	34.1 ± 1.8	35.7 ± 1.7
N_{obs}	36	35
$A \times \epsilon$	3.4%	3.7%
$\sigma(l^+l^-\gamma)$ (pb)	$4.8 \pm 0.8 \pm 0.3$	$4.4 \pm 0.8 \pm 0.2$

The cross section $\sigma(l\nu\gamma)$ is measured in the kinematic range $\Delta R(l,\gamma) > 0.7$ and $E_T^\gamma > 7$ GeV with $\sigma = (N_{obs} - N_{bg})/(A \times \epsilon \times \int \mathcal{L}\, dt) = (N_{obs} - N_{bg})/N_{sig} \times \sigma_{SM}$. Here, $\int \mathcal{L}\, dt$ is the integrated luminosity, A is the acceptance, ϵ is the selection efficiency and σ_{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 η range using extrapolations based upon the SM expectation [19]. Combining the electron and muon channel, assuming lepton universality, and taking into account correlations of the systematic uncertainties, yields $\sigma(l\nu\gamma) = 18.1 \pm 3.1$ pb. The theoretical prediction for this cross section is 19.3 ± 1.4 pb.

The cross section $\sigma(l^+l^-\gamma)$ is measured in the kinematic range $\Delta R(l,\gamma) > 0.7$, $E_T^\gamma > 7$ GeV and $M(l^+,l^-) > 40$ GeV/c^2. We follow the same procedure as for the $W\gamma$ analysis and obtain the cross section listed in Table II. The measured cross sections are determined for the full Z decay phase space, dilepton mass range $M(l^+,l^-) > 40$ GeV/c^2 and photon η range using extrapolations based upon the SM expectation [19]. The combined electron and muon result is $\sigma(l^+l^-\gamma) = 4.6 \pm 0.6$ pb. The theoretical prediction for this cross section is 4.5 ± 0.3 pb.

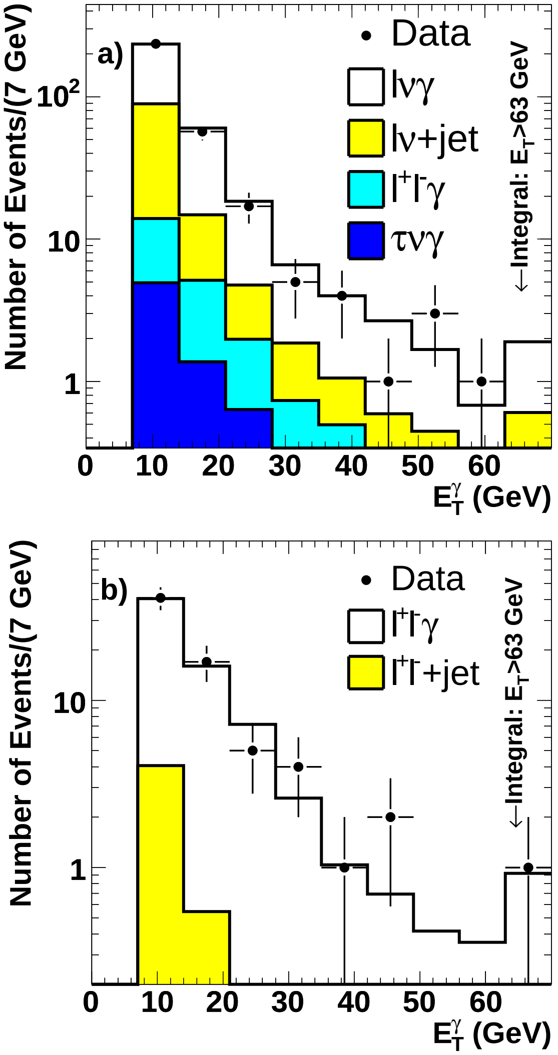

FIG. 1. Photon transverse energy spectrum, E_T^γ, for a) $W\gamma$ and b) $Z\gamma$ candidates selected in the leptonic decay channel. The data are compared with the SM expectations for signal and background with the histograms added cumulatively. In both figures the last bin contains all events with $E_T^\gamma > 63$ GeV.

In addition to these cross section measurements, we compare the SM predictions for several kinematic variables with the data for $E_T^\gamma > 7$ GeV and $\Delta R(l,\gamma) > 0.7$. We choose the E_T^γ and final state mass spectra since these are sensitive tests of SM predictions. The transverse energy of the photon in $W\gamma$ and $Z\gamma$ production is shown in Figure 1. Figure 2 shows the cluster transverse mass [22], $M_T(l\gamma,\nu)$, for $W\gamma$ events and the invariant mass of the (l^+,l^-,γ) system, $M(l^+,l^-,\gamma)$, for $Z\gamma$ events. The data are in good agreement with the SM expectations for both processes. The event with the highest E_T photon, ob-

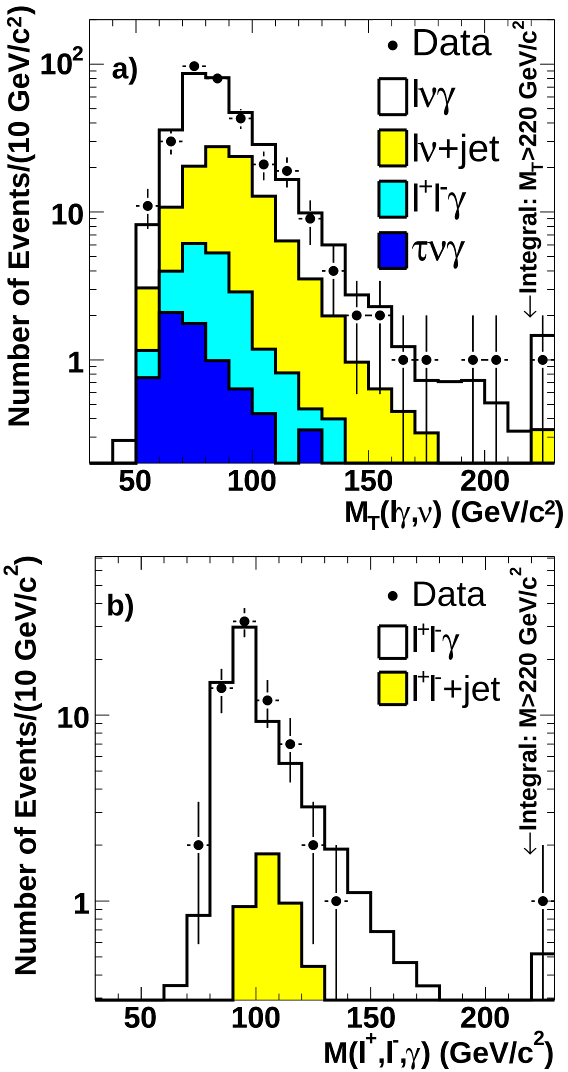

FIG. 2. a) The cluster transverse mass of the lepton-photon-missing E_T system for $W\gamma$ candidates, and b) the invariant mass of the lepton-lepton-photon system for $Z\gamma$ candidates. The data are compared with the SM expectations for signal and background with the histograms added cumulatively. In both figures the last bin contains all events with masses above 220 GeV/c^2.

served in the $e^+e^-\gamma$ channel with $E_T^\gamma = 141$ GeV and $M(e^+, e^-, \gamma) = 382$ GeV/c^2, is consistent with the rate expected from SM predictions.

In summary, we have measured $W\gamma$ and $Z\gamma$ production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ 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^γ 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 with SM predictions.

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