

$W\gamma$ Production and Limits on Anomalous $WW\gamma$ Couplings in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We measure the cross section and the difference in rapidities between photons and charged leptons for inclusive $W(\rightarrow l\nu) + \gamma$ production in $e\gamma$ and $\mu\gamma$ final states. Using data corresponding to an integrated luminosity of 4.2 fb^{-1} collected with the D0 detector at the Fermilab Tevatron Collider, the measured cross section times branching fraction for the process $p\bar{p} \rightarrow W\gamma + X \rightarrow l\nu\gamma + X$ and the distribution of the charge-signed photon-lepton rapidity difference are found to be in agreement with the standard model. These results provide the most stringent limits on anomalous $WW\gamma$ couplings for data from hadron colliders: $-0.4 < \Delta\kappa_\gamma < 0.4$ and $-0.08 < \lambda_\gamma < 0.07$ at the 95% C.L.

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The electroweak component of the standard model (SM) has been remarkably successful in describing experimental results. The $WW\gamma$ vertex is one example of self-interactions of electroweak bosons that are a consequence of the non-Abelian $SU(2)_L \times U(1)_Y$ gauge symmetry of the SM. In this Letter we use the process $p\bar{p} \rightarrow W\gamma \rightarrow l\nu\gamma$ ($l = e, \mu$) to study this vertex and to search for any anomalous departure from SM $WW\gamma$ couplings.

An effective Lagrangian parameterizes the $WW\gamma$ couplings with two parameters, κ_γ and λ_γ [1,2], under the assumptions of electromagnetic gauge invariance, charge conjugation (C), parity (P), and CP conservation. The κ_γ and λ_γ couplings are related to the magnetic dipole and electric quadrupole moments of the W boson [1,2]. In the SM, $\kappa_\gamma = 1$ and $\lambda_\gamma = 0$, and it is customary to introduce into the notation the difference $\Delta\kappa_\gamma \equiv \kappa_\gamma - 1$.

To assure that the $W\gamma$ cross section does not violate unitarity, a form factor, with a common scale Λ for each

non-SM coupling parameter, is introduced to modify the terms as $a_0 \rightarrow a_0/(1 + \hat{s}/\Lambda^2)^2$, where $a_0 = \kappa_\gamma, \lambda_\gamma$, and \hat{s} is the square of the partonic center-of-mass energy. In this analysis, the scale Λ is set to 2 TeV. Contributions from anomalous couplings will increase the $W\gamma$ production cross section and yield photons of higher energy than in the SM process[2].

In the SM, tree level production of a photon in association with a W boson occurs due to prompt $W\gamma$ production via the diagrams shown in Fig. 1 or via final state radiation, where a lepton from the W boson decay radiates a photon. It is an important property of the SM prediction at leading order that the interference between the amplitudes in Fig. 1 produces a zero in the total $W\gamma$ yield at a specific angle θ^* between the W boson and the incoming quark [3] in the $W\gamma$ rest frame. Since in hadronic collisions the longitudinal momenta of neutrinos from W decay cannot be measured, the angle θ^* at which the radiation amplitude is zero is

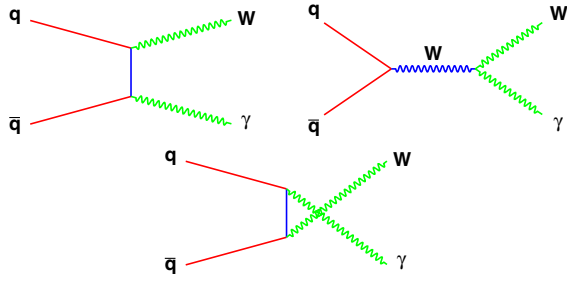


FIG. 1 (color online). Feynman diagrams for prompt $W\gamma$ production.

difficult to measure directly. However, the radiation amplitude zero is also visible in the charge-signed photon-lepton rapidity difference as a dip around $-1/3$ [4].

In this Letter, we present measurements of the cross section and the distribution of the charge-signed photon-lepton rapidity difference for $W\gamma$ production as well as a search for anomalous $WW\gamma$ couplings, using data corresponding to an integrated luminosity of $4.2 \pm 0.3 \text{ fb}^{-1}$ collected by the D0 detector at $\sqrt{s} = 1.96 \text{ TeV}$ at the Fermilab Tevatron Collider. $W\gamma$ production has been studied previously at hadron colliders [5–9]. The latest published D0 results [8] represent the most stringent constraints on anomalous $WW\gamma$ couplings, and include the first study of the charge-signed photon-lepton rapidity difference at a hadron collider. The results of the present analysis provide a significant improvement in the sensitivity to $WW\gamma$ couplings through a nearly factor of 6 increase in data and by using an artificial neural network for photon identification.

The D0 detector [10] comprises a central tracking system in a 2 T superconducting solenoidal magnet, surrounded by a central preshower (CPS) detector, a liquid-argon sampling calorimeter, and an outer muon system. The tracking system, a silicon microstrip tracker and a scintillating fiber tracker, provides coverage for charged particles in the pseudorapidity range $|\eta| < 3$ [11]. The CPS is located immediately before the inner layer of the calorimeter, and has about 1 r.l. of absorber, followed by several layers of scintillating strips. The calorimeter consists of a central sector (CC) with coverage of $|\eta| < 1.1$, and two end calorimeters (ECs) covering up to $|\eta| \approx 4.2$. The electromagnetic (EM) section of the calorimeter is segmented into four longitudinal layers (EM*i*, $i = 1, 4$) with transverse segmentation of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ [11], except in EM3, where it is 0.05×0.05 . The muon system resides beyond the calorimeter and consists of a layer of tracking detectors and scintillation trigger counters before the 1.8 T iron toroidal magnet, followed by two similar layers after the toroid. The coverage of the muon system corresponds to $|\eta| < 2$.

Candidate events with the W boson decaying into an electron and a neutrino are collected using a suite of single-electron triggers. The electrons are selected by requiring

an EM cluster in either the CC ($|\eta| < 1.1$) or ECs ($1.5 < |\eta| < 2.5$) with transverse energy $E_T > 25 \text{ GeV}$ contained within a cone of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.2$ centered on the axis of the EM shower. At least 90% of the cluster energy must be deposited in the EM section of the calorimeter. In addition, electron candidates are required to be isolated in the calorimeter and in the tracking detector, have a shower shape consistent with that of an electron, and a spatial match to a track. A multivariate likelihood discriminant, which includes information from the spatial track match, must be consistent with that for an electron. An artificial neural network is trained using information from the tracker, calorimeter, and CPS detectors to further reject background from jets misidentified as electrons. The event missing transverse energy, \cancel{E}_T [12], must exceed 25 GeV, and the transverse mass of the W boson, M_T [13], must exceed 50 GeV. To reduce the background from $Z/\gamma^* \rightarrow ee$, where an electron is misidentified as a photon because of tracking inefficiency, the azimuthal angle between the electron and photon is required to be $\Delta\phi_{e\gamma} < 2$.

Candidate events with the W boson decaying into a muon and a neutrino are also collected using a suite of single-muon triggers. The muons are required to be within $|\eta| < 1.6$, isolated in both the tracker and the calorimeter, and matched to a track with transverse momentum $p_T > 20 \text{ GeV}$. To suppress the $Z/\gamma^* \rightarrow \mu\mu$ background, the \cancel{E}_T in the event must exceed 20 GeV, M_T must exceed 40 GeV, and there must be no additional muons or tracks with $p_T > 15 \text{ GeV}$.

The photon candidates in both the electron and muon channels are required to have transverse energy $E_T^\gamma > 15 \text{ GeV}$ within a cone of radius $\Delta R = 0.2$ centered on the EM shower. In addition, photon candidates are required to be either in the CC ($|\eta| < 1.1$) or ECs ($1.5 < |\eta| < 2.5$) and must satisfy the following requirements: (i) at least 90% of the cluster energy is deposited in the EM calorimeter; (ii) the calorimeter isolation variable $I = [E_{\text{tot}}(0.4) - E_{\text{EM}}(0.2)]/E_{\text{EM}}(0.2) < 0.15$, where $E_{\text{tot}}(0.4)$ is the total energy in a cone of radius $\Delta R = 0.4$ and $E_{\text{EM}}(0.2)$ is the EM energy in a cone of radius $\Delta R = 0.2$; (iii) the energy-weighted cluster width in the EM3 layer is consistent with that for an EM shower; (iv) the scalar sum of the p_T of all tracks, $p_{T_{\text{trk}}}^{\text{sum}}$, originating from the interaction point in an annulus of $0.05 < \Delta R < 0.4$ around the cluster is less than 2.0 (1.5) GeV for a cluster in the CC (ECs); (v) the EM cluster is not spatially matched to either a reconstructed track, or to energy depositions in the silicon microstrip tracker or scintillating fiber tracker detectors that lie along the trajectory of an electron [14]; and (vi) the output of an artificial neural network (O_{NN}) [15], that combines information from a set of variables sensitive to differences between photons and jets in the tracking detector, the calorimeter, and the CPS detector, is larger than 0.75. To suppress background from final state

radiation, the photon and the lepton must be separated by $\Delta R_{l\gamma} > 0.7$, and the three-body transverse mass [4] of the photon, lepton, and missing transverse energy must exceed 110 GeV. Furthermore, events are accepted only if the $p\bar{p}$ interaction vertex is reconstructed within 60 cm of the center of the D0 detector along the beam axis.

Trigger and lepton identification efficiencies are measured using $Z \rightarrow ll$ ($l = e, \mu$) data. Parts of the photon identification efficiency which rely exclusively on calorimeter information are also determined using $Z \rightarrow ee$ data. The photon track veto efficiencies are determined using $Z \rightarrow l^+l^-\gamma$ events, where the photons are radiated from charged leptons in Z boson decays. The selected data sample is contaminated by the following backgrounds: (i) $W + \text{jet}$ events with a jet misidentified as a photon; (ii) “ leX ” events with a lepton, electron, and \cancel{E}_T with the electron misidentified as a photon; (iii) $Z\gamma \rightarrow ll\gamma$ events containing an unidentified lepton; and (iv) $W\gamma \rightarrow \tau\nu\gamma$ events with the τ decaying to e or μ . A Monte Carlo (MC) simulation is used to model the $W\gamma$ signal, as well as the $Z\gamma \rightarrow ll\gamma$ and $W\gamma \rightarrow \tau\nu\gamma$ backgrounds. The signal is simulated using the Baur and Berger leading order event generator [2], interfaced to PYTHIA [16] for subsequent parton showering and hadronization. The shape and normalization of the signal E_T^γ spectrum are reweighted to the next-to-leading order prediction [4]. The acceptance of the kinematic and geometric requirements for this analysis is calculated using this E_T^γ -weighted signal MC calculations. The $Z\gamma \rightarrow ll\gamma$ and $W\gamma \rightarrow \tau\nu\gamma$ background processes are simulated with PYTHIA. All MC events are generated using the CTEQ6L1 [17] parton distribution functions, followed by a GEANT [18] simulation of the D0 detector. To accurately model the effects of multiple $p\bar{p}$ interactions and detector noise, data from random $p\bar{p}$ crossings are overlaid on the MC events. The instantaneous luminosity spectrum of these overlaid events is matched to that of the events used in the data analysis. The simulated events are processed using the same reconstruction code that is used for data.

$W + \text{jet}$ production is the dominant background for both the electron and muon channels. To estimate this background, the fraction of jets that pass the photon selection criteria but fail either the $p_{T,\text{trk}}^{\text{sum}}$ or the shower width requirement, as determined by using a multijet data sample, is parameterized as a function of E_T^γ and η_γ . The background from $W + \text{jet}$ production is then estimated starting from a data sample obtained by reversing the requirements either on $p_{T,\text{trk}}^{\text{sum}}$ or on the shower width requirement, and applying the same parameterization. As a cross-check, the $W + \text{jet}$ background is also estimated through a fit to the O_{NN} distribution in data, using MC templates constructed from generated photon and jet events. The result is in good agreement with that obtained from the ratio method. The “ leX ” background is also estimated from an orthogonal data sample by requiring the electron candidate to be

TABLE I. Number of predicted and observed events with statistical and systematic uncertainties.

	$e\nu\gamma$ channel	$\mu\nu\gamma$ channel
$W + \text{jet}$	33.9 ± 3.7	64.6 ± 6.8
leX	1.1 ± 0.6	2.1 ± 0.7
$Z\gamma \rightarrow ll\gamma$	1.8 ± 0.3	17.6 ± 1.9
$W\gamma \rightarrow \tau\nu\gamma$	2.3 ± 0.3	5.4 ± 0.6
Total background	39.1 ± 3.8	89.7 ± 7.2
SM $W\gamma$ prediction	150.9 ± 13.8	282.1 ± 25.4
Data	196	363

matched to a high-quality track. The number of “ leX ” events is obtained by using this orthogonal data sample, taking into account the ratio of the track—matching inefficiency to the track matching efficiency obtained from $Z \rightarrow ee$ data. Events in the electron channel that have both the electron and photon in the ECs are excluded from this analysis, because of the poor acceptance for signal and the presence of overwhelming background. The number of predicted and observed events in both the electron and muon channels are summarized in Table I.

The sources of systematic uncertainty that affect the signal acceptance and the background normalization include: integrated luminosity (6.1%), trigger efficiency (5%), electron identification (3%), muon identification (3%), photon identification (3%), track veto (0.9%), signal acceptance due to uncertainties on parton distribution functions (0.4%), predicted cross sections for $Z\gamma \rightarrow ll\gamma$ (4%) and $W\gamma \rightarrow \tau\nu\gamma$ (3%), and estimation of $W + \text{jet}$ background (10%).

The measured cross sections multiplied by the branching fractions for $\sigma(p\bar{p} \rightarrow W\gamma + X \rightarrow l\nu\gamma + X)$ for photons with $E_T^\gamma > 15$ GeV and $\Delta R_{l\gamma} > 0.7$ are

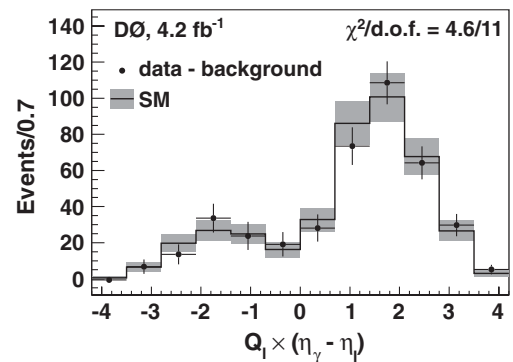


FIG. 2. The charge-signed photon-lepton rapidity difference ($Q_l \times (\eta_\gamma - \eta_l)$, where Q_l is the charge of the lepton) in background-subtracted data compared to the SM expectation for the combined electron and muon channels. The background-subtracted data are shown as black points with error bars representing their total uncertainties. The SM signal prediction is given by the solid line, with the shaded area representing its uncertainty.

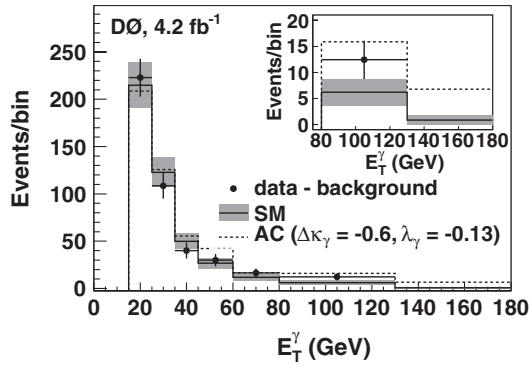


FIG. 3. Photon transverse energy distributions for background-subtracted data compared to the expectation for the SM and for one choice of anomalous couplings for the combined electron and muon channels. The background-subtracted data are shown as black points with uncertainties representing the associated statistical and systematic uncertainties. The SM prediction is given by the solid line, with the shaded area representing its uncertainty. The effect of one example of anomalous couplings is represented by the dashed line. The last E_T^γ bin shows the sum of all events with $E_T^\gamma > 130$ GeV. The inset shows the distributions in the last two bins of E_T^γ .

$7.9 \pm 0.7(\text{stat}) \pm 0.7(\text{syst})$ pb for the electron channel, and $7.4 \pm 0.5(\text{stat}) \pm 0.7(\text{syst})$ pb for the muon channel. The detector resolution effects that would result in some of the events failing the $E_T^\gamma > 15$ GeV and $\Delta R_{l\gamma} > 0.7$ requirements at the generator level but passing them at the reconstructed-object level have been taken into account. Taking into account the correlation in systematic uncertainties, the combined results yield a cross section multiplied by the branching fraction of $7.6 \pm 0.4(\text{stat}) \pm 0.6(\text{syst})$ pb, which is in good agreement with the SM expectation of 7.6 ± 0.2 pb.

The charge-signed photon-lepton rapidity difference for the combination of the two channels is shown in Fig. 2. Because of significant charge misidentification of EC electrons, only events with CC electrons are used in Fig. 2. The background-subtracted data are in good agreement with the SM prediction, and a χ^2 test comparing the background-subtracted data with the SM prediction yields 4.6 for 11 degrees of freedom.

The photon E_T^γ distributions in Fig. 3 show good agreement between data and the SM prediction. Therefore, we use the photon E_T^γ spectra to derive limits on anomalous $WW\gamma$ trilinear couplings using a binned likelihood fit to data. The likelihood is calculated assuming Poisson statistics for the number of events in the data, the signal, and the background. All systematic uncertainties on sources of background, efficiencies, and luminosity are assumed to be Gaussian, and their correlations are taken into account in the fit. The 95% C.L. limits on the $WW\gamma$ coupling parameters are shown in Fig. 4, with the contour defining the two-dimensional exclusion limits. The one-dimensional 95% C.L. limits are $-0.4 < \Delta\kappa_\gamma < 0.4$ and

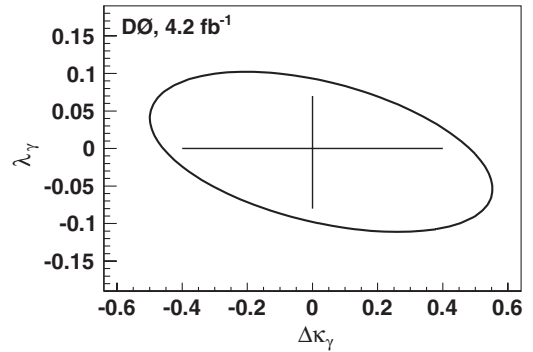


FIG. 4. Limits on the $WW\gamma$ coupling parameters $\Delta\kappa_\gamma$ and λ_γ . The ellipse represents the two-dimensional 95% C.L. exclusion contour. The one-dimensional 95% C.L. limits are shown as the vertical and horizontal lines.

$-0.08 < \lambda_\gamma < 0.07$, which are obtained by setting one coupling parameter to the SM value and allowing the other to vary.

In summary, we have studied $W\gamma$ production using data corresponding to an integrated luminosity of 4.2 fb^{-1} collected by the D0 detector at the Fermilab Tevatron Collider. The cross section multiplied by the branching fraction for the process $p\bar{p} \rightarrow W\gamma + X \rightarrow l\nu\gamma + X$ is measured to be $7.6 \pm 0.4(\text{stat}) \pm 0.6(\text{syst})$ pb, which is in good agreement with the SM expectation of 7.6 ± 0.2 pb for $E_T^\gamma > 15$ GeV and $\Delta R_{l\gamma} > 0.7$. The distribution of the charge-signed photon-lepton rapidity difference has a minimum near $Q_l \times (\eta_\gamma - \eta_l) = -1/3$, consistent with the SM prediction. We also set the most stringent limits on anomalous $WW\gamma$ couplings at a hadron collider, with the one-dimensional parameters restricted to $-0.4 < \Delta\kappa_\gamma < 0.4$ and $-0.08 < \lambda_\gamma < 0.07$, at the 95% C.L.

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