Wγ production and limits on anomalous WWγ couplings in p̅p collisions at √s = 1.96 TeV

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 cross section multiplied by the branching fraction for the process $p\bar{p} \rightarrow W\gamma + X \rightarrow l\nu\gamma + X$, measured to be $15.8 \pm 0.8$ (stat.) $\pm 1.2$ (syst.) $pb$, 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, $\kappa_\gamma$ and $\lambda_\gamma$, under the assumptions of electromagnetic gauge invariance, charge conjugation ($C$), parity ($P$) and $CP$ conservation. The $\kappa_\gamma$ and $\lambda_\gamma$ 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 $\Lambda$ for each non-SM coupling parameter, is introduced to modify the
terms as $a_0 \to a_0/(1 + \hat{s}/\Lambda^2)^2$, 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 $\Lambda$ 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 (FSR), where a lepton from the $W$ boson decay radiates a photon. It is an important property of the SM prediction at leading order (LO) that the interference between the amplitudes in Fig. 1 produces a zero in the total $W\gamma$ yield at a specific angle $\theta^*$ between the $W$ boson and the incoming quark $q$ in the $W\gamma$ rest frame. Since in hadronic collisions the longitudinal momenta of neutrinos from $W$ decay cannot be measured, the angle $\theta^*$ at which the radiation amplitude is zero is difficult to measure directly. However, the radiation amplitude zero (RAZ) is also visible in the charge-signed photon-lepton rapidity difference as a dip around $-1/3$ [4].

![Feynman diagrams for prompt $W\gamma$ production.](image)

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 ± 0.3 fb$^{-1}$ collected by the D0 detector at $\sqrt{s} = 1.96$ TeV at the Fermilab Tevatron Collider. $W\gamma$ production has been studied previously at hadron colliders [5–9]. The latest published D0 result [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 six 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 (SMT) and a scintillating fiber tracker (CFT), 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 one radiation length 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 (EC) covering up to $|\eta| = 4.2$. 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 $0.05 \times 0.05$. The muon system resides beyond the calorimeter and consists of a layer of tracking detectors and scintillation trigger counters before 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 EC ($1.5 < |\eta| < 2.5$) with transverse energy $E_T > 25$ 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, $E_T^{miss}$ [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 $Z/\gamma \to ee$, 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 $p_T > 20$ GeV. To suppress the $Z/\gamma \to \mu\mu$ background, the $E_T$ in the event must exceed 20 GeV, $M_T$ must exceed 40 GeV, and there must be no additional muons or tracks with $p_T > 15$ GeV.

The photon candidates in both the electron and muon channels are required to have transverse energy $E_T > 15$ 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 EC ($1.5 < |\eta| < 3$).
events. The instantaneous luminosity spectrum of these
 monte carlo (MC) simulation is used to model the
 \( Z\gamma \) distribution functions (PDF), followed by a
 MC events are generated using the CTEQ6L1 [17] par-
 calorimeter information are also determined using
 backgrounds: (i) selected data sample is contaminated by the following
 radiated from charged leptons in
 interaction point in an annulus of 0
 ground is also estimated from an orthogonal data sam-
 and jet events. The result is in good agreement with
 that obtained from the ratio method. The “leX” back-
 ground is also estimated from an orthogonal data sam-
 by requiring the electron candidate to be 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 EC 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 in-
clude: 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 PDF (0.4%), predicted cross sections for \( Z\gamma \rightarrow ll\gamma \) (4%) and \( W\gamma \rightarrow \tau\nu\gamma \) (3%), and estimation of W+jet background (10%).

The measured cross sections multiplied by the branching
fractions for \( \sigma(pp \rightarrow W\gamma + X \rightarrow l\nu\gamma + X) \) for photons with \( E_T > 8 \text{ GeV} \) and \( \Delta R_{\gamma l} > 0.7 \) are
16.6 ± 1.4 (stat.) ± 1.5 (syst.) pb for the electron channel, and 15.5 ± 1.0 (stat.) ± 1.4 (syst.) pb for the

<table>
<thead>
<tr>
<th>Channel</th>
<th>Predicted</th>
<th>Observed</th>
</tr>
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<tbody>
<tr>
<td>( W+\text{jet} )</td>
<td>33.9 ± 3.7</td>
<td>64.6 ± 6.8</td>
</tr>
<tr>
<td>( leX )</td>
<td>1.1 ± 0.6</td>
<td>2.1 ± 0.7</td>
</tr>
<tr>
<td>( Z\gamma \rightarrow ll\gamma )</td>
<td>1.8 ± 0.3</td>
<td>17.6 ± 1.9</td>
</tr>
<tr>
<td>( W\gamma \rightarrow \tau\nu\gamma )</td>
<td>2.3 ± 0.3</td>
<td>5.4 ± 0.6</td>
</tr>
</tbody>
</table>

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

TABLE I: Number of predicted and observed events with statistical and systematic uncertainties.
muon channel. Taking into account the correlation in systematic uncertainties, the combined results yield a cross section multiplied by the branching fraction of $15.8 \pm 0.8$ (stat.) $\pm 1.2$ (syst.) pb, which is in good agreement with the SM expectation of $16.0 \pm 0.4$ pb \[4, 5\].

The charge-signed photon-lepton rapidity difference for the combination of the two channels is shown in Fig. 2. Because of significant charge mis-identification 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 $\chi^2$ test comparing the background-subtracted data with the SM prediction yields 4.6 for 11 degrees of freedom.

The photon $E_T^\gamma$ distributions in Fig. 3 show good agreement between data and the SM prediction. Therefore, we use the photon $E_T^\gamma$ 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 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 $-0.08 < \lambda_\gamma < 0.07$, 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 $15.8 \pm 0.8$ (stat.) $\pm 1.2$ (syst.) pb, which is in good agreement with the SM expectation of $16.0 \pm 0.4$ pb for $E_T^\gamma > 8$ 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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[11] Pseudorapidity is defined as $\eta = -\ln[\tan(}\theta/2\rbracket$, where $\theta$ is the polar angle relative to the proton beam direction. $\phi$ is defined to be the azimuthal angle in the plane transverse to the proton beam direction.