Measurement of W-Photon Couplings in p-$\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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We report on a study of W + photon production in approximately 20 pb^{-1} of p-$\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV recorded with the Collider Detector at Fermilab. Our results are in good agreement with standard model expectations and are used to obtain limits on anomalous CP-conserving $WW\gamma$ couplings of $-2.3 < \Delta\kappa < 2.2$ for $\lambda = 0$ and $-0.7 < \lambda < 0.7$ for $\Delta\kappa = 0$ at 95% C.L. We obtain the same limits for CP-violating couplings. These results provide limits on the higher-order electromagnetic moments of the W boson of $0.8 < g_W < 3.1$ for $q_W^e = 1$ and $-0.6 < q_W^e < 2.7$ for $g_W = 2$ at 95% C.L.

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In the standard model of electroweak interactions the W, Z, and photon are assumed to be fundamental gauge bosons. The most general description of the couplings between the W and γ, consistent with Lorentz and electromagnetic gauge invariance, can be expressed in terms of two CP-conserving and two CP-violating couplings (momentum-dependent form factors) κ, λ and $\tilde{\kappa}$, $\tilde{\lambda}$, respectively [1]. The tree level standard model predictions for these couplings are $\Delta\kappa \equiv \kappa - 1 = \lambda = \tilde{\kappa} = \tilde{\lambda} = 0$. The values of the $WW\gamma$ couplings at zero momentum transfer (the static limit) are related to the higher-order electromagnetic (EM) moments of the W boson by

$$\mu_W = \frac{e}{2M_W}(2 + \Delta\kappa + \lambda) = \frac{e}{2M_W} g_W \text{ (magnetic dipole moment)},$$

$$Q_W^e = -\frac{e}{M_W^2}(1 + \Delta\kappa - \lambda) = -\frac{e}{M_W^2} q_W^e \text{ (electric quadrupole moment)},$$

$$d_W = \frac{e}{2M_W}(\tilde{\kappa} + \tilde{\lambda}) = \frac{e}{2M_W} \delta_W \text{ (electric dipole moment)},$$

$$Q_W^m = -\frac{e}{M_W^2}(\tilde{\kappa} - \tilde{\lambda}) = -\frac{e}{M_W^2} q_W^e \text{ (magnetic quadrupole moment)}.$$

In p-$\bar{p}$ collisions, information about the strength and nature of these couplings can be extracted from events in which an energetic photon is produced in association with a W boson. Three types of processes give rise to photon production in W events: radiation from an initial-state quark, from the W itself, and from the charged lepton of the W decay [2]. Interference between the amplitudes for these processes guarantees gauge invariance in the framework of the standard model. Deviations from the standard model $WW\gamma$ couplings would lead to unitarity violations in the cross section at high center of mass energies in the $W\gamma$ system, signaling the presence of new physics at this energy scale. This would manifest itself most dramatically as an excess of W production with high transverse energy (E_T) photons. In a recent publication [3] we reported the observation of W and Z bosons produced in association with a photon, using the data from the 1988–1989 Collider run at Fermilab. The measured $W\gamma$ cross section times branching ratio was found to be consistent with the standard model expectation but left room for sizable deviations, as indicated by the 95% confidence limits (C.L.) for the two CP-conserving couplings: $-6.0 \leq \Delta\kappa \leq 6.4$ (for $\lambda = 0$) and $-2.4 \leq \lambda \leq 2.3$ (with $\Delta\kappa = 0$). The UA2 Collaboration has reported comparable limits [4]. In this Letter, we present results on $WW\gamma$ couplings measured from fitting the E_T distribution of the photons, using the roughly 5 times larger data sample from the 1992–1993 Collider run.

The Collider Detector at Fermilab (CDF) has been described elsewhere [5]. The components most relevant to this analysis include (i) a time projection chamber for measuring the position of the primary vertex, (ii) the central tracking chamber (CTC), in a 1.4 T solenoidal magnetic field, used for momentum measurement, (iii) electromagnetic and hadronic calorimeters for energy and missing transverse energy measurement, and (iv) chambers surrounding the calorimeters for muon identification. The calorimeters are arranged in projective towers and cover the pseudorapidity range $|\eta| \leq 1.1$ (central calorimeters), $1.1 \leq |\eta| \leq 2.4$ (plug calorimeters), and $2.4 \leq |\eta| \leq 4.2$ (forward calorimeters). In the EM calorimeters, finely segmented proportional chambers (CES) used to measure transverse electromagnetic shower profiles are placed at a depth of approximately 6 radiation lengths. The $W \rightarrow e\nu$ candidates were selected [6] by requiring a central ($|\eta| \leq 1.05$) isolated electron or positron with transverse energy $E_T \geq$ 20 GeV and missing transverse energy $\not{E}_T > 20$ GeV. The $W \rightarrow \mu\nu$ candidates were selected [7] by requiring an isolated track in the CTC with $P_T \geq 20$ GeV/c matched to a track stub in our central muon chambers ($|\eta| \leq 0.6$), and the presence of $\not{E}_T > 20$ GeV. The inclusive W event sample consisted of 13 920 events in the electron channel and 6 105 events in the muon channel, corresponding to integrated luminosities of 19.6 ± 0.7 pb^{-1} and 18.6 ± 0.7 pb^{-1}, respectively.

These event samples were examined for photon candidates, defined as clusters of electromagnetic energy with no track pointing at it, with $E_T \geq 7$ GeV in the central EM calorimeter. The direction of the photon was defined as the line between the collision point from which the charged W decay lepton emerged and the center of the EM shower as measured with the CES. To reduce the contribution from photons radiated by the charged W decay lepton, the angular separation between the photon and the lepton $\Delta R_{\ell\gamma}$ was required to be greater than 0.7, where $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$. To reduce background arising from hadronic jets, the E_T in a cone of $\Delta R = 0.4$ [E_T (0.4)] around the photon candidate was required to be less than 15% of the photon E_T, and the sum of the P_T of charged tracks within this cone [P_T (0.4)] was required to be less than 2.0 GeV/c. To reduce the background from neutral hadrons, the ratio of energy deposited by the photon candidate in the hadronic calorimeter to that in the electromagnetic calorimeter was required to be less than $0.055 + 0.00045 \times E$, where E was the total energy of the candidate in GeV. To suppress π^0 and multiphoton backgrounds, the transverse shower profile measured in the CES was required to be consistent with that of a single photon. Events having more than one CES cluster with energy >1.0 GeV within the region of the electron shower were rejected. With these selection criteria 18 (7) $W + \gamma$ candidates were found in the electron (muon) samples.

After these stringent isolation requirements, the remaining backgrounds consist either of W events where the photon candidate arises from a hadronic jet fragmenting into a single isolated neutral meson that decays to multiple photons or of events from $Z + \gamma$ or $(W \rightarrow \nu\tau) + \gamma$ production. The jet fragmentation background was estimated by measuring the fraction of jets in an independent sample of inclusive jet events ("QCD" sample) that satisfy our photon selection criteria and apply that fraction to the inclusive W samples. This assumes that the probability for a jet to be misidentified as an isolated photon is the same for jets in the QCD and W samples, an assumption motivated by the similarity of the E_T spectra and gluon-jet fractions in the two samples [8]. The QCD sample studied also contained genuine single photons from Compton-type processes. The number of such photons was estimated using a CES shower shape analysis [9], and the background estimate was corrected. The ratio of the number of remaining photon candidates to the number of jets gave a P_T dependent probability factor $P(\text{jet} \rightarrow \gamma)$ of 8×10^{-4} at 9 GeV/c P_T, which decreased exponentially to 10^{-4} at 25 GeV/c P_T. The overall jet fragmentation background for the combined electron and muon decay channels was estimated to be $6.5 \pm 1.2 \pm 1.6$ events. The first error reflects the statistical uncertainty in estimating the contribution of genuine single photons to the QCD sample. The second error represents systematic uncertainties, including the method used to estimate the number of genuine photons, variations in the binning of the photon P_T distribution, and comparisons with Monte Carlo estimates of jet rejection using a $W +$ jet calculation implemented in the VECBOS program [10].

Contributions arising from $Z\gamma$ events where one of the leptons from the Z decay is not detected were suppressed by searching for a second isolated charged particle with $P_T \geq 10$ GeV/c. If the invariant mass of the lepton and this additional particle were consistent with the mass of the Z, the event would be rejected. The processes $(W \longrightarrow \tau\nu_\tau) + \gamma$ and $(W \longrightarrow \tau\nu_\tau) +$ jet also contribute to the background in the electron and muon $W\gamma$ data samples when the τ decays to an electron or muon, respectively. The total background from all of these sources was estimated by Monte Carlo simulations to be 0.7 ± 0.1 and 1.3 ± 0.2 events in the electron and muon channels, respectively.

The fraction of genuine photons accepted by the E_T (0.4) and P_T (0.4) isolation requirements was estimated from an examination of the inclusive W samples. This was done by measuring the probability that these quantities, calculated for a cone of $\Delta R = 0.4$ placed randomly in an event, would satisfy the selection criteria. The photon efficiencies for the other selection criteria were determined using studies of a calorimeter module in an electron test beam. The acceptance for the E_T (0.4) requirement ranges from 90% for 7 GeV E_T photons to 99% for $E_T > 25$ GeV. All other selection criteria are independent of the photon E_T. The product of all E_T-independent efficiencies, combined with the photon conversion probability of (6.6 ± 0.5)%, gives a combined efficiency of (81.2 ± 2.3)%.

These efficiencies were used in a Monte Carlo calculation that modeled the detector acceptance and included smearing effects from finite resolution. A $W\gamma$ Monte Carlo program was used to generate simulated electron, muon, and tau $W\gamma$ events [11]. The MRS D'_- [12] structure functions, which best match the most recent charge asymmetry measurements of W decays by CDF [13], were used for the event generation. Figure 1 compares kinematic distributions of the data to the sum of the standard model prediction and the estimated background. The absence of an excess of high P_T photons in Fig. 1(a) rules out large deviations from standard model couplings. The falling $\Delta R_{l\gamma}$ distribution in Fig. 1(b) indicates that a large fraction of the signal is from radiative $W \longrightarrow l\gamma\nu$ decays. The cluster transverse mass [14] distribution in Fig. 1(c), on the other hand, contains 4 events with $M_{CT}^W > 95$ GeV/c^2, which are primarily due to *direct* W-photon production in the process p-$\bar{p} \longrightarrow W\gamma X$ and background.

The experimental result for the $W\gamma$ cross section times branching ratio in the combined electron and muon channels for central photons with $E_T^\gamma \geq 7$ GeV and $\Delta R_{l\gamma} \geq 0.7$ is $\sigma B(W\gamma)_{(e+\mu)} = 13.2 \pm 4.2$ (stat) ± 1.5 (syst) pb, while the standard model predictions give $\sigma B(W\gamma)_{\mathrm{SM}} = 18.6 \pm 2.8$ (stat + syst) pb. The systematic uncertainty in the measurement comes dominantly from the uncertainty in the background determination, the detector efficiencies, and the integrated luminosity. The theoretical prediction depends on the choice of structure functions, the Q^2 scale, and the P_T distribution assumed for the $W\gamma$ system. In view of the absence of a complete theoretical calculation (including soft gluon resummation) of the $W\gamma$ P_T spectrum, we assumed the transverse momentum distribution of the $W\gamma$ system to be the same as the inclusive W P_T distribution measured by CDF [15]. An overall systematic (or theoretical) uncertainty of 15% arises from varying the choice of the structure functions (12.6%), the Q^2 scale (1.0)%, and the P_T (8.8%).

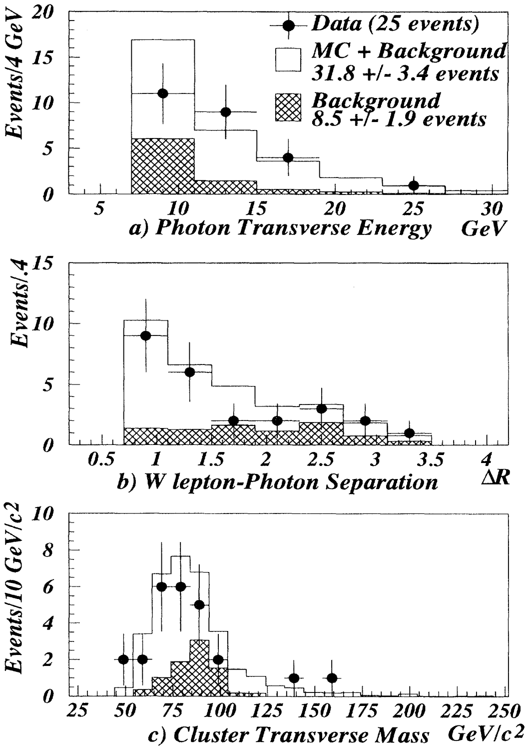

FIG. 1. (a) E_T distribution of central photon candidates in $W\gamma$ events. (b) The angular separation $\Delta R_{\ell\gamma}$ between the photon candidate and the charged lepton from the W decay. (c) The cluster transverse mass M_{CT}^W of the W decay leptons and the photon. The prediction for the standard model signal has been added to the background prediction.

Limits on $WW\gamma$ anomalous couplings were evaluated by comparing the observed photon P_T distribution to the sum of the Monte Carlo signal prediction plus the estimated background. The likelihood that this sum could fluctuate to the observed number of events was calculated for each P_T bin using Poisson statistics. The predicted number of events was convoluted with a Gaussian distribution to include the effects of systematic uncertainties. The 68%, 90%, and 95% confidence contours in $\Delta\kappa$ vs λ are shown in Fig. 2(a). The sensitivity to anomalous

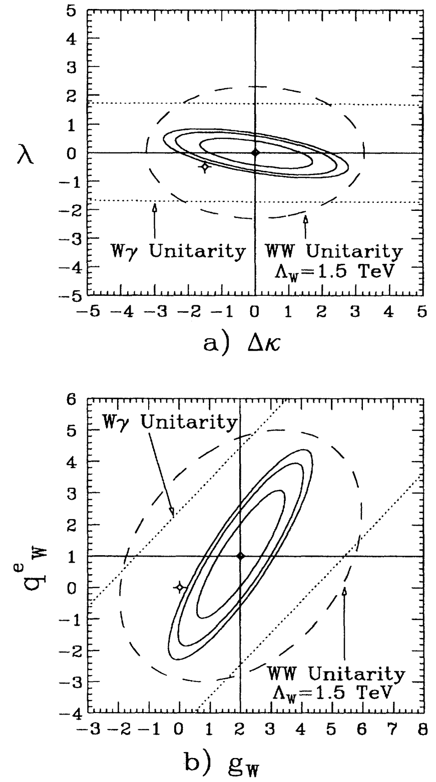

FIG. 2. (a) The limits on CP-conserving $WW\gamma$ couplings and on (b) static W multipole moments for the combined $e + \mu$ $W\gamma$ sample. The solid ellipses show the 68%, 90%, and 95% C.L. limit contours. The W^+W^- and $W\gamma$ unitarity limits for a form factor scale $\Lambda_W = 1.5$ TeV are indicated by dashed and dotted curves, respectively. The open points denote the point where both multipole moments vanish.

couplings has increased by a factor of 3 over previous results [3,4], but no deviation from standard model expectations is observed. The effect of a dipole form factor with a form factor scale $\Lambda_W = 1.5$ TeV has been included in this analysis. The experimental results are insensitive to the choice of the form factor scale for $\Lambda_W > 0.3$ TeV. Tree level S-matrix unitarity [16] imposes constraints on the allowed values of $\Delta\kappa$ and λ in the $p\text{-}\bar{p} \rightarrow XW\gamma$ and XW^+W^- processes, as shown in Fig. 2 for $\Lambda_W = 1.5$ TeV. Unitarity is violated in the regions outside these contours. Our 95% C.L. limit contour is well inside the unitarity constraints.

We obtain direct limits on CP-conserving $WW\gamma$ anomalous couplings of $-2.3 < \Delta\kappa < 2.2$ for $\lambda = 0$ and $-0.7 < \lambda < 0.7$ for $\Delta\kappa = 0$ at 95% C.L. Similarly, we obtain direct limits on CP-violating anomalous couplings $\tilde{\kappa}$ and $\tilde{\lambda}$, which are within 3% of those obtained for $\Delta\kappa$ and λ, respectively. The limit contours of the quantities g_W and q^e_W are displayed in Fig. 2(b). We obtain $0.8 < g_W < 3.1$ for $q^e_W = 1$ and $-0.6 < q^e_W < 2.7$ for $g_W = 2$ at 95% C.L. We also obtain direct limits on CP-violating electric dipole and magnetic quadrupole moments d_W and Q^m_W. The related quantities δ_W and q^m_W are within 3% of those obtained for $g_W - 2$ and $q^e_W - 1$, respectively.

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