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First Study of the Radiation-Amplitude Zero in $W\gamma$ Production and Limits on Anomalous $WW\gamma$ Couplings at $\sqrt{s} = 1.96$ TeV

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We present results from a study of $p\bar{p} \rightarrow W\gamma + X$ events utilizing data corresponding to 0.7 fb^{-1} of integrated luminosity at $\sqrt{s} = 1.96$ TeV collected by the D0 detector at the Fermilab Tevatron Collider. We set limits on anomalous $WW\gamma$ couplings at the 95% C.L. The one-dimensional 95% C.L. limits are $0.49 < \kappa_\gamma < 1.51$ and $-0.12 < \lambda_\gamma < 0.13$. We make the first study of the charge-signed rapidity difference between the lepton and the photon and find it to be indicative of the standard model radiation-amplitude zero in the $W\gamma$ system.

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Self-interactions of the electroweak bosons are a consequence of the $SU(2)_L \times U(1)_Y$ gauge symmetry of the standard model (SM). In this Letter, we investigate the $WW\gamma$ vertex by studying the production of $p\bar{p} \to W\gamma \to \ell\nu\gamma + X$ events where ℓ is an electron or a muon. At leading order (LO), the SM allows $q\bar{q}' \to W\gamma$ production in which a photon radiates off an incoming quark (initial state radiation) or is directly produced from the $WW\gamma$ vertex. In the SM, these two cases involve three amplitudes where each alone violates unitarity, but together interfere to give a finite cross section. This interference leads to a radiation-amplitude zero (RAZ) in the angular distribution of the photon. In this Letter, we set limits on non-SM $WW\gamma$ couplings and present a first measurement of the destructive interference indicative of the RAZ in the $W\gamma$ system.

Non-SM $WW\gamma$ couplings will give rise to an increase in the $W\gamma$ production cross section over the SM prediction, particularly for energetic photons. CP-conserving couplings may be parameterized by an effective Lagrangian [1,2] with two parameters, κ_γ and λ_γ, related to the magnetic dipole and electric quadrupole moments of the W boson. In the SM, $\kappa_\gamma = 1$ and $\lambda_\gamma = 0$. The effective Lagrangian with non-SM couplings will violate unitarity at high energies, and so a form factor with a scale Λ is introduced to modify the coupling parameters with $a_0 \to a_0/(1 + \hat{s}/\Lambda^2)^2$ where $a_0 = \kappa_\gamma$, λ_γ, and $\sqrt{\hat{s}}$ is the $W\gamma$ invariant mass. We set Λ to 2 TeV [3].

A general consequence of gauge theories is that any four-particle tree amplitude involving one or more massless gauge bosons may be factorized into a charge dependent part and a spin and polarization dependent part. The charge dependent part will lead to the amplitude vanishing at a particular point in phase space. For a $2 \to 2$ process, as is the case for $W\gamma$, this effect is evident as a zero in the production amplitude in the angular distribution of the photon [2]. The RAZ manifests itself as a dip in the charge-signed rapidity difference, $Q_\ell \times \Delta y$, between the photon and the charged lepton from the W boson decay [4]. In the massless limit regime, the rapidity difference can be approximated by the pseudorapidity difference [5], which can be very precisely measured. The SM predicts that the dip minimum depends on the quark electric charges and lies at $Q_\ell \times \Delta\eta \approx -1/3$. In the case of anomalous couplings the location of the dip minimum does not change, instead the dip may become more shallow or disappear entirely.

$W\gamma$ production has been studied previously at hadron colliders [6]. The limits set by the most recent previous D0 analysis represented the most stringent constraints on anomalous $WW\gamma$ couplings obtained by direct observation of $W\gamma$ production. The present analysis uses more than 4 times as much data as well as photons in the end-cap calorimeter, and thus has an increased sensitivity for the study of $Q_\ell \times \Delta\eta$. The D0 detector [7] is used in this study to observe $p\bar{p} \to \ell\nu\gamma + X$ ($\ell = e$ or μ) in collisions at $\sqrt{s} = 1.96$ TeV at the Fermilab Tevatron collider. The data samples correspond to integrated luminosities of 717 ± 44 pb^{-1} and 662 ± 40 pb^{-1} for the electron and muon channels, respectively.

Candidate events with the W boson decaying into an electron and a neutrino are collected with a suite of single electron triggers. The reconstructed electron is required to be in the central ($|\eta_{\mathrm{det}}| < 1.1$) or end-cap ($1.5 < |\eta_{\mathrm{det}}| < 2.5$) calorimeters [5], have transverse energy $E_T > 25$ GeV, be isolated in the calorimeter, have a shower shape consistent with that of an electromagnetic object, and match a track reconstructed in the central tracking system. The missing transverse energy, $\not\!\!E_T$, must exceed 25 GeV. To reduce final state radiation of photons from leptons, the reconstructed W transverse mass must exceed 50 GeV$/c^2$. Furthermore, to suppress background from $Z \to ee$ events with an electron misidentified as a photon, the two-body invariant mass of the electron and photon must be outside the mass window 87–97 GeV$/c^2$. The optimized window limits are asymmetric about the Z boson mass because the expected signal will have more events below the Z boson mass than above it.

Candidate events with the W boson decaying into a muon and a neutrino are collected with a suite of single muon triggers. The reconstructed muon is required to be within $|\eta_{\mathrm{det}}| < 1.6$, isolated in the central tracking system and the calorimeter and be associated with a central track with $p_T > 20$ GeV$/c$. The event $\not\!\!E_T$ must exceed 20 GeV and there must be no additional isolated tracks with $p_T > 15$ GeV$/c$ as well as no additional muons. The muon momentum is measured by the curvature of the track in the central tracking system.

Photons are identified with the same requirements in both channels. The photon must have $E_T > 9$ GeV and be in the central ($|\eta_{\mathrm{det}}| < 1.1$) or end-cap ($1.5 < |\eta_{\mathrm{det}}| < 2.5$) calorimeter. It must be isolated in the calorimeter and tracker, have a shower shape consistent with that of an electromagnetic object, have an associated cluster in the preshower detector, and, if in the central region, project back to a position along the beam axis within 10 cm of the primary vertex. The photon and the lepton must be separated in $\eta - \phi$ space by $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.7$. To further suppress final state radiation, the three-body transverse mass (M_{T3}) of the photon, lepton, and missing transverse energy must exceed 120 GeV$/c^2$ and 110 GeV$/c^2$ for the electron and muon channels, respectively.

Kinematic and geometric acceptances are determined using Monte Carlo (MC) events. For the acceptances to be meaningful, they are measured with respect to reference

TABLE I. Summary of event yields. When uncertainties are shown, the first is statistical and the second is systematic. When only one uncertainty is shown, it is systematic.

	$e\nu\gamma$ channel	$\mu\nu\gamma$ channel
Luminosity	720 ± 44 pb^{-1}	660 ± 40 pb^{-1}
Acceptance $\times$ efficiency	0.063 ± 0.003	0.045 ± 0.003
W + jet background	$34 \pm 3.8 \pm 3.1$	$18 \pm 2.9 \pm 1.9$
ℓeX background	$17 \pm 2.7 \pm 1.3$	$2.7 \pm 1.3 \pm 0.2$
$W \to \tau$ background	$1.1 \pm 0.1 \pm 0.1$	$1.4 \pm 0.2 \pm 0.1$
$Z\gamma$ background	—	$3.8 \pm 0.53 \pm 0.42$
Candidate events	180	83
Measured signal	$130 \pm 14 \pm 3.4$	$57 \pm 8.8 \pm 1.8$
SM prediction	120 ± 12	77 ± 9.4

kinematic requirements of $E_T^\gamma > 9$ GeV, $M_{T3} > 90$ GeV$/c^2$, and $\Delta R > 0.7$ (MC samples were produced with much looser requirements). A LO simulation [8] of $W\gamma$ production is used, which includes the contributions from initial and final state radiation as well as the $WW\gamma$ trilinear vertex. To compensate for the effects of next-to-leading order (NLO) corrections on the E_T^γ spectrum, a NLO MC calculation [9] is used, and an E_T^γ-dependent K factor is calculated and applied to the LO spectra. The detector resolutions are applied using a parameterized simulation.

Electron and muon identification efficiencies are determined with large $Z \to ee$ or $Z \to \mu\mu$ samples from the data. The photon detection efficiency is determined by the full GEANT [10] detector simulation and is verified with $Z\gamma$ data. In these events, the photon is radiated from a final state lepton and so the three-body mass of the photon and the leptons should reconstruct the Z boson mass. The reconstruction efficiency from the GEANT MC program is scaled to match the measured efficiency from the $Z\gamma$ process in data. The acceptance times efficiency values described here are shown in Table I.

Backgrounds to $W\gamma$ production include W + jet events where the jet is misidentified as a photon, "ℓeX" events with a lepton, electron, and $\not{E}_T$ where the electron is misidentified as a photon, $Z\gamma \to \ell\ell\gamma$ events where a lepton is lost; and $W\gamma \to \tau\nu\gamma$. The W + jet background dominates both channels and is determined from data. The rate at which a jet is misidentified as a photon is calculated from a large multijet sample in which the jets under study are required to have a large fraction of their energy deposited in the electromagnetic layers of the calorimeter. This rate is calculated as a function of E_T and η_{det}. The rate is then applied to a normalization sample of W + jet events where the jets satisfy the same criteria as in the multijet sample. To determine the ℓeX background, the track isolation requirement is removed from the photon and a matched track is required. The measured tracking efficiencies are then used to estimate this background contribution. The $Z\gamma$ and $W\gamma \to \tau\nu\gamma \to e(\mu)\nu\nu\gamma$ backgrounds are estimated from MC calculations. The $Q_\ell \times \Delta\eta$ distribution of the total background lacks any statistically significant structure. A summary of the background estimates and the observed $W\gamma$ candidate events are shown in Table I.

Since the observed event yields are consistent with the SM predictions, limits on anomalous $WW\gamma$ trilinear couplings are determined using the combined E_T^γ spectrum from both channels (Fig. 1). Limits are set by generating E_T^γ spectra for different values of the coupling parameters κ_γ and λ_γ, and then calculating the likelihood they represent the data. The 95% C.L. limit contour is found numerically by integrating the likelihood surface and finding the minimum contour that represents 95% of the volume. One-dimensional 95% C.L. limits are calculated by setting one coupling parameter to the SM value and allowing the other to vary. These limits, shown in Fig. 2, are $0.49 < \kappa_\gamma < 1.51$ and $-0.12 < \lambda_\gamma < 0.13$.

The background-subtracted $Q_\ell \times \Delta\eta$ distribution for the combined electron and muon channels is shown in

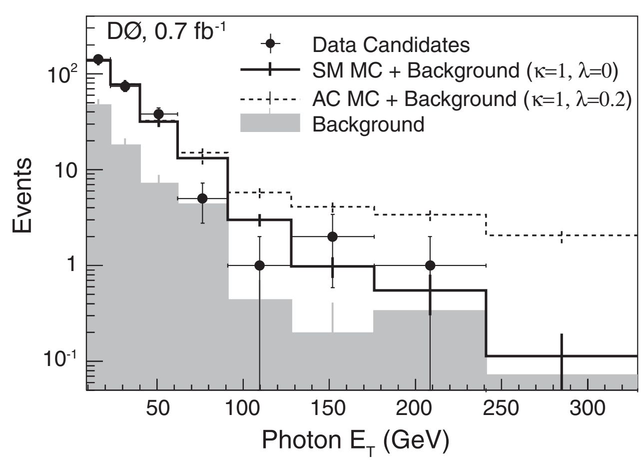

FIG. 1. The photon transverse energy spectra for the SM (solid line), an anomalous coupling (AC) point (dashed line), combined electron and muon channel data candidates (black points), and the background estimate (shaded histogram). Uncertainties are shown as error bars on the points, lines, and histograms. The last bin includes overflows.

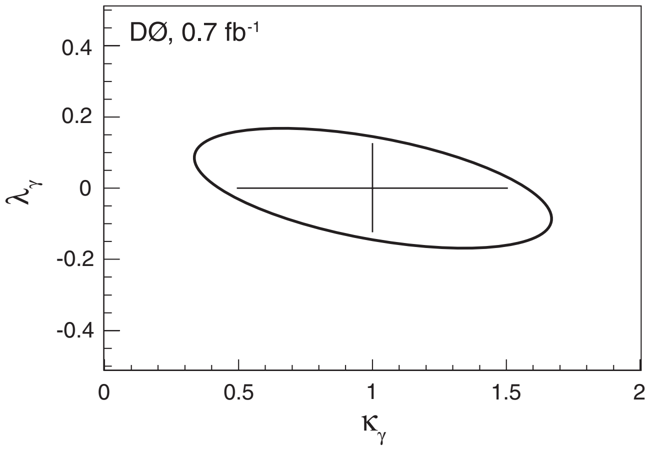

FIG. 2. The ellipse is the 95% C.L. limit contour in $\kappa_\gamma - \lambda_\gamma$ space. One-dimensional 95% C.L. limits are shown as the horizontal and vertical bars.

Fig. 3. To perform a statistical test for the presence of a dip, the distribution is divided into two bins whose edges are determined by the $Q_\ell \times \Delta\eta$ distribution generated in SM Monte Carlo calculations. The bins are chosen to be adjacent and of equal width such that one samples the majority of events in the dip and the other samples the smaller of the local maxima (see the inset in Fig. 4). We define a test statistic R to be the ratio of the integral number of events in the dip bin to the integral number of events in the maximum bin. This ratio will be at least one if there is no dip (unimodal distribution), and less than one if there is a dip. For the combined background-subtracted data $Q_\ell \times \Delta\eta$, this ratio test gives a value of 0.64.

We first compare this observed R value from the data to an ensemble of 10^4 MC SM pseudoexperiments where all statistical and systematic fluctuations are included. For the SM, 28% of the experiments have a ratio of 0.64 or greater. In order to evaluate the significance of the observed data R value, we select an anomalous coupling value which provides a $Q_\ell \times \Delta\eta$ distribution that minimally exhibits no dip—the minimal unimodal hypothesis (MUH). Minimal specifically means a class of distributions on the boundary of bimodal and unimodal distributions. The distribution chosen here corresponds to $\kappa_\gamma = 0$, $\lambda_\gamma = -1$ (zero magnetic dipole moment of the W boson). Anomalous couplings increase the event yield as well, but since we are only concerned with the distribution shape, we normalize this distribution to the number of events predicted by the SM. For this MUH case, only 45 experiments out of 10^4 have an R value of 0.64 or smaller due to a random fluctuation. These distributions are shown in Fig. 4. If transformed into a Gaussian significance, this probability corresponds to 2.6σ. This result is the first study of the $Q_\ell \times \Delta\eta$ distribution and is indicative of the RAZ in $W\gamma$ production.

In summary, we have studied $W\gamma$ production and set 95% C.L. limits on anomalous trilinear gauge couplings at $0.49 < \kappa_\gamma < 1.51$ and $-0.12 < \lambda_\gamma < 0.13$. These limits are the most stringent set at a hadron collider for this final state. We also performed the first study of the radiation-amplitude zero in the charge-signed rapidity difference between the lepton and the photon. The probability that this measurement would arise from a minimal unimodal

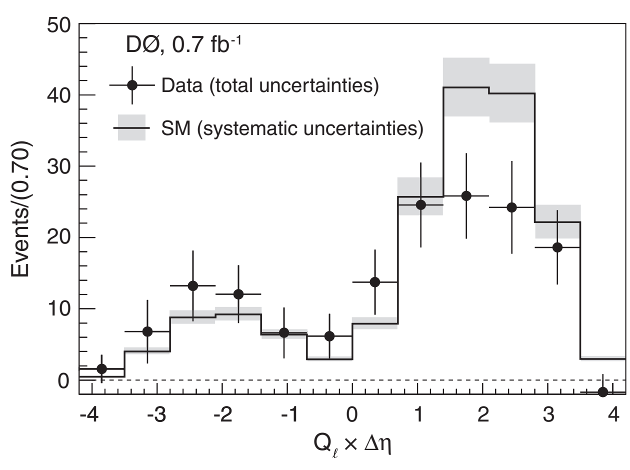

FIG. 3. The background-subtracted charge-signed rapidity difference for the combined electron and muon channels. The black points and error bars represent background-subtracted data with its associated uncertainties (statistical and from the subtraction procedure), and the shaded areas are the systematic uncertainties on the SM prediction (including on efficiencies and acceptances). The solid line is the distribution from the SM. A χ^2 test comparing the data and SM using the full covariance matrix yields 17 for 12 degrees of freedom, indicating good agreement.

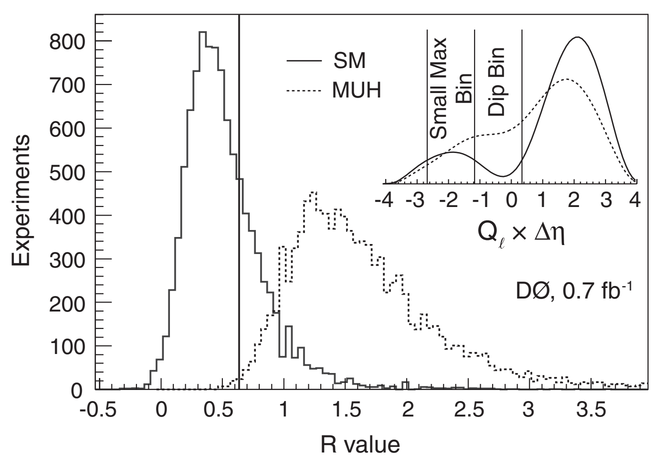

FIG. 4. Distributions of the R-test statistic for the SM ensemble (solid line) and the MUH ensemble (dashed line). The vertical line indicates the measured value from the data. The inset plot indicates the positions of the two bins used for the R test as determined by a fit to the SM $Q_\ell \times \Delta\eta$ distribution (solid line). For comparison, a fit to the MUH $Q_\ell \times \Delta\eta$ distribution is shown as the dashed line.

hypothesis is smaller than $(4.5 \pm 0.7) \times 10^{-3}$ and is indicative of the radiation-amplitude zero in $W\gamma$ production.

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