Limits on Anomalous Trilinear Gauge Couplings in Zγ Events from p ¯ p Collisions at $\sqrt{s} = 1.96$ TeV

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Using $Z\gamma$ candidate events collected by the CDF detector at the Tevatron Collider, we search for potential anomalous (non-standard-model) couplings between the $Z$ boson and the photon. $Z\gamma$ couplings vanish at tree level and are heavily suppressed at higher orders; hence any evidence of couplings indicates new physics. Measurements are performed using data corresponding to an integrated luminosity of $4.9\ f b^{-1}$ in the $Z \to \nu \bar{\nu}$ decay channel and $5.1\ f b^{-1}$ in the $Z \to l^+ l^-$ ($l = \mu, e$) decay channels. The combination of these measurements provides the most stringent limits to date on $Z\gamma$ trilinear gauge couplings. Using an energy scale of $\Lambda = 1.5\ TeV$ to allow for a direct comparison with previous measurements, we find limits on the $CP$-conserving parameters that describe $Z\gamma$ couplings to be $|h_4^Z| < 0.022$ and $|h_5^Z| < 0.0009$. These results are consistent with standard model predictions.

Studies of trilinear couplings between the gauge bosons ($W$, $Z$, $\gamma$) test the standard model (SM) description of gauge sector interactions and provide sensitivity to physics beyond the SM through examination of production rates and kinematics [1–6]. In the case of neutral couplings, $ZZ\gamma$ and $Z\gamma\gamma$ vertex interactions vanish at tree level and, while allowed via internal particle loops, are highly suppressed in the SM. However, these trilinear gauge couplings can be non-negligible if loop contributions occur via non-SM particles. Models such as those incorporating compositeness or supersymmetry can alter the predicted cross section and production kinematics of $Z\gamma$ events [7–10].

In the SM, given the suppression of $ZZ\gamma$ and $Z\gamma\gamma$ couplings, the production of $Z\gamma$ events is dominated by production of a $Z$ boson along with the radiation of a photon off either an incoming parton or a $Z$ decay product.
These production mechanisms are interesting in their own right, serving as an important background to searches for new physics (e.g., in gauge-mediated supersymmetry breaking models [11]) and Higgs boson searches. In this Letter, the production properties of $Z\gamma$ events are compared to SM predictions, and limits are set on anomalous trilinear gauge couplings.

The measurements of $Z\gamma$ couplings are performed with $p\bar{p}$ collision data at $\sqrt{s} = 1.96$ TeV from the Tevatron Collider using the Collider Detector at Fermilab (CDF). We seek two types of $Z\gamma$ events: those where the $Z$ decays to charged leptons (by identifying lepton candidate pairs and a prompt photon [12] with large transverse energy $E_T$ [13]), and those where the $Z$ decays to neutrinos (by identifying an event with only a solitary, prompt, high-$E_T$ photon). In the former case, data corresponding to an integrated luminosity of 5.1 fb$^{-1}$ are used; in the latter, 4.9 fb$^{-1}$. These measurements use over twice as much data as the previous published CDF result [1] and incorporate looser muon selection requirements. As no significant disagreement is found between the SM prediction and the data, we set limits that are not only far more restrictive than those measured in [1], but are approximately half the magnitude of the previous best published limits [4].

In beyond-the-SM scenarios with enhanced $Z\gamma$ couplings, not only does the $Z\gamma$ production cross section increase, but also the photon $E_T$ spectrum is modified due to an enhancement in the production of high-$E_T$ photons [10]. We take advantage of this enhancement by comparing the photon $E_T$ distribution in data to both SM and beyond-the-SM predictions. Binned maximum likelihood measurements of the coupling parameters that describe $Z\gamma$ interactions in the Lagrangian are performed. We calculate separate likelihoods for the $Z \rightarrow l^+l^-$ and $Z \rightarrow \nu\bar{\nu}$ samples and combine the likelihoods to produce the final result.

The CDF detector is covered in detail elsewhere [14,15]. The transverse momenta ($p_T$) of charged particles are measured by an eight-layer silicon strip detector [16] and a 96-layer drift chamber (COT) [17] inside a 1.4 T magnetic field. The COT provides tracking coverage with high efficiency for the pseudorapidity range $|\eta| < 1$ [13]. Electromagnetic and hadronic calorimeters surround the tracking system. They are segmented in a projective tower geometry and measure the energies 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 [18]. The calorimeters are surrounded by drift chambers that detect muons.

The measurements of anomalous trilinear gauge coupling parameters in the $Z \rightarrow l^+l^-$ and $Z \rightarrow \nu\bar{\nu}$ decay channels differ both in event selection and background estimation. For the $Z\gamma \rightarrow l^+l^-\gamma$ decay channel we identify events containing $Z \rightarrow \mu^+\mu^-$ and $Z \rightarrow e^+e^-$. The measurements of anomalous trilinear gauge coupling parameters in the $Z \rightarrow l^+l^-$ and $Z \rightarrow \nu\bar{\nu}$ decay channels differ both in event selection and background estimation. For the $Z\gamma \rightarrow l^+l^-\gamma$ decay channel we identify events containing $Z \rightarrow \mu^+\mu^-$ and $Z \rightarrow e^+e^-$. The estimated contribution of SM $Z\gamma$ events is derived from Monte Carlo (MC) simulations that use the Buur-Berger package at the generator level [10] and PYTHIA [20] for particle showering. This method yields a prediction of $87.2 \pm 7.8Z\gamma$ events that pass our selection requirements, where the uncertainty is dominated by the uncertainty on the luminosity and the predicted cross section. The non-$Z\gamma$ events that pass these selection requirements result from hadronic jets being reconstructed as prompt photons and leptons (more commonly electrons). This background is estimated by calculating separate probabilities for a jet to mimic a photon or lepton as a function of jet $E_T$, and applying them to jets in events to which all our requirements have been applied except those pertaining to the mimicked particle. For photons and electrons, these
probabilities are calculated by taking the ratio of the number of individual photon or electron candidates to the number of jets in a sample of data events where only the presence of at least one jet is required. The number of photon and electron candidates is corrected for the expected contribution of true photons or electrons in this sample. We estimate the probability for a false muon candidate from the number of dimuon Z decay candidates in which both muon candidates have the same charge. Overall, the non-Zγ background contribution is very low: of the 91 events that pass our requirements, less than one event involving a mimicked photon or lepton is expected.

In order to identify Zγ candidate events in the Z \rightarrow \nu \bar{\nu} decay channel, we require solitary high-\textit{E}_{T} photons and a transverse energy imbalance of at least 50 GeV. In order to discriminate against W boson contamination in our sample, we reject events containing any tracks with \textit{p}_{T} > 10 GeV, any electron candidates with \textit{E}_{T} > 15 GeV, or any muon candidates with \textit{p}_{T} > 10 GeV/c. Additionally, we reject events that have any jets with \textit{E}_{T} > 15 GeV in order to reduce the mismeasurement of missing transverse energy. The primary SM source for photons passing these requirements is Zγ events in which the Z has decayed to a pair of neutrinos, as shown in Table I. The method of estimating the expected number of Zγ events is the same as that used for the Z \rightarrow l^{+}l^{-} candidate sample.

The primary source of non-Zγ events in the final Zγ \rightarrow \nu \bar{\nu}γ candidate sample is cosmic ray interactions. High-\textit{E}_{T} photons from cosmic rays leave large transverse energy imbalances in our detector, mimicking the presence of neutrinos. Therefore, additional event requirements are applied to reduce the contributions from cosmic ray events. First, we require that the energy deposited in the electromagnetic calorimeter appear within a timing window centered on the p\bar{p} interaction. Second, we use a relevance vector machine (RVM) multivariate discriminator [22] to distinguish whether a photon came from a collision or a noncollision source; the three inputs used for the RVM discriminator are the \phi angle between the photon candidate and the closest muon candidate (if any), the ratio of energies from the photon candidate in the electromagnetic and hadronic calorimeters, and the ratio of energies from the electromagnetic shower profile detector and the electromagnetic calorimeter. We use photons outside the timing window to train the RVM for noncollision sources, and photons recoiling against jets to train for collision sources. The RVM discriminator reduces the contribution from cosmic ray events by an additional 90%. Finally, we require the event to have a reconstructed vertex of at least three tracks from a p\bar{p} interaction. After applying these selection requirements, we have 85 candidate events in our sample. Despite the anticosmic ray requirements, cosmic ray events remain the second largest contributor to our sample, after Zγ events.

We model two other major categories of non-Zγ events: one in which a charged lepton from W \rightarrow e\nu, W \rightarrow \mu\nu, or W \rightarrow \tau\nu decay is reconstructed as a photon, and the other in which a true photon is produced but another object (e.g., a lepton) is lost or only partially reconstructed, creating a large transverse energy imbalance. For the former case, the rate at which electrons are reconstructed as photons in the detector has been calculated using events with an electron and photon pair candidate that has an invariant mass near the mass of the Z, i.e., events in which the photon candidates are almost entirely electrons in actuality. The rate at which μ’s and τ’s are reconstructed as photons is taken from MC. For the latter case, which encompasses Wγ \rightarrow l\nuγ events in which a lepton is lost and γγ events in which a photon is lost, a two-step process is used to calculate the expected number of events. First, events in data are selected such that we obtain a very pure sample of one of the aforementioned event types in which there is no lost object. Then, we calculate the fraction of the corresponding events in MC in which an object is not detected, and this fraction is used to scale the photon \textit{E}_{T} distribution of the data events so as to provide an estimate of this background’s photon \textit{E}_{T} distribution in the signal sample. An exception to this method is the case in which a τ is lost; due to the difficulty of reliably identifying τ candidates, this background is estimated purely from MC simulations. Further details on these methods of background prediction can be found in [23], a CDF analysis which used very similar event requirements. We see excellent agreement between the SM predictions and the data in the control regions of 15 < \textit{E}_{T} < 40 GeV (Z \rightarrow l^{+}l^{-} case) and 70 < \textit{E}_{T} < 100 GeV (Z \rightarrow \nu \bar{\nu} case).

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**TABLE I.** SM expected contributions to the Zγ \rightarrow \nu \bar{\nu}γ candidate sample. Uncertainties shown are systematic only and thus exclude the statistical uncertainties.

<table>
<thead>
<tr>
<th>Process</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zγ \rightarrow \nu \bar{\nu}γ</td>
<td>52.8 ± 4.6</td>
</tr>
<tr>
<td>Cosmic</td>
<td>14.9 ± 1.4</td>
</tr>
<tr>
<td>W \rightarrow e\nu</td>
<td>3.9 ± 0.8</td>
</tr>
<tr>
<td>W \rightarrow \mu\nuγ</td>
<td>1.6 ± 0.3</td>
</tr>
<tr>
<td>Wγ \rightarrow e\nuγ</td>
<td>1.1 ± 1.1</td>
</tr>
<tr>
<td>Wγ \rightarrow \mu\nuγ</td>
<td>1.8 ± 1.3</td>
</tr>
<tr>
<td>Wγ \rightarrow \tau\nuγ</td>
<td>4.5 ± 1.3</td>
</tr>
<tr>
<td>γγ</td>
<td>5.3 ± 1.9</td>
</tr>
<tr>
<td>SM total</td>
<td>85.9 ± 5.6</td>
</tr>
<tr>
<td>Data</td>
<td>85</td>
</tr>
</tbody>
</table>
Assuming gauge and Lorentz invariance, eight parameters are needed to describe $Z\gamma$ couplings, denoted by $h_{10}^\gamma$ where $V$ is either a $Z$ or a $\gamma$ and the index $i$ runs from 1 to 4; these parameters are all zero at tree level [10]. Interaction amplitudes are linear in these parameters. Indices 1 and 2 represent $CP$-violating terms while indices 3 and 4 represent $CP$-conserving terms. We assume $CP$ conservation in these interactions by setting $h_{10}^\gamma = h_{20}^\gamma = 0$ and we investigate the possibility of nonzero values for $h_{30}^\gamma$ and $h_{40}^\gamma$, corresponding to electric dipole and magnetic quadrupole transition moments [24]. In order to preserve unitarity at large incoming parton center-of-mass energy $\sqrt{s}$, an $s$-dependent form factor is used to suppress the coupling, constructed as $h_{n}^\gamma(s) = \frac{h_{n}^0}{(1 + s/\Lambda^2)^{n/2}}$, where $n = i$ for $h_{30}^\gamma$ and $h_{40}^\gamma$ [10]. The parameter $\Lambda$ describes the predicted energy scale of the new physics that creates anomalous $Z\gamma$ couplings.

For a given set of anomalous coupling parameter values, we compute a likelihood for the $E_T$ distribution. Hence, we have $\prod_{j=1}^{N} L(x_j|h_n^\gamma)$, where $x_j$ represents the number of entries in the $j$th of $N$ bins in our $E_T$ distribution and $h_n^\gamma$ denotes the coupling parameter being measured (the other three being held fixed at zero). The bin-by-bin likelihood $L$ is simply the Poisson probability of the number of observed entries given the expected number of entries for the value of $h_n^\gamma$. This limit method requires a predicted $E_T$ distribution for each combination of the four coupling parameters. To create these distributions, we produce $Z\gamma$ MC events at the generator level using the Baur-Berger package [10]. Modeling the particle showering process and detector response in MC separately for every parameter value is computationally impractical. To mimic fully simulated MC events we first determine the efficiency for a generated event to pass all of the event requirements as a function of generator-level $E_T^\gamma$ and $|\eta|$; these functions are derived from a SM MC sample which has used the full simulation of the detector. Because of the correlation between $E_T^\gamma$ and the $Z$ kinematics, we create and combine separate templates for the cases of central-central, central-forward, and forward-forward lepton pairs, “central” denoting $0 < |\eta| < 1.1$ and “forward” denoting $1.1 < |\eta| < 2.8$. We then apply this efficiency function to generator-level MC samples to get the expected $E_T^\gamma$ distributions. The final prediction is the sum of this $Z\gamma$ prediction with the predictions of the non-$Z\gamma$ backgrounds.

In Fig. 1, for both the $Z \to l^+l^-$ and $Z \to \nu\bar{\nu}$ cases, the $E_T^\gamma$ distributions in data are compared to the SM prediction and beyond-the-SM predictions; it can be seen that the production of high-$E_T$ photons is far more likely in the beyond-the-SM cases compared to the SM case. The uncertainty bands shown for the SM predictions illustrate the systematic uncertainties on those predictions. These uncertainties are dominated by the 7% uncertainty on the theoretical $Z\gamma$ cross section [25] and the 6% uncertainty on the luminosity [26]; the other sources are the reconstructed photon’s energy scale and efficiency, as well as uncertainties on the number of non-$Z\gamma$ background events. The effect of these systematic uncertainties on the limits is negligible—of the order of a couple of percent of the limit values.

With the likelihood distribution for a given $h_n^\gamma$, taking a flat Bayesian prior in $h_n^\gamma$ allows us to set Bayesian credibility limits on the parameter. These limits are defined as the values of $h_n^\gamma$ which demarcate the central 95% of the integral of the likelihood distribution. The resulting allowed ranges for the strength of anomalous couplings are shown in Table II. The values $\Lambda = 1.2$ TeV and $\Lambda = 1.5$ TeV have been chosen to allow direct comparisons with earlier CDF [1] and D0 [4] results, respectively. We see no evidence for anomalous couplings.

In conclusion, we find that the $E_T^\gamma$ distribution of photons produced in association with $Z$ bosons in both the $Z \to \nu\bar{\nu}$ and $Z \to l^+l^-$ decay channels in a data sample corresponding to an integrated luminosity of approximately 5 fb$^{-1}$ is consistent with SM couplings. We place 95% Bayesian...
TABLE II. Allowed ranges (95% Bayesian credibility limits) of anomalous $Z\gamma$ couplings for $\Lambda = 1.2$ and 1.5 TeV using notation from Ref. [10]. Each parameter’s limits are set assuming the other three parameters have values fixed at 0.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$(\Lambda = 1.2 \text{ TeV})$</th>
<th>$(\Lambda = 1.5 \text{ TeV})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_3^{0}$</td>
<td>$-0.024, 0.027$</td>
<td>$-0.020, 0.021$</td>
</tr>
<tr>
<td>$h_4^{0}$</td>
<td>$-0.0013, 0.0013$</td>
<td>$-0.0009, 0.0009$</td>
</tr>
<tr>
<td>$h_3^{\gamma}$</td>
<td>$-0.026, 0.026$</td>
<td>$-0.022, 0.020$</td>
</tr>
<tr>
<td>$h_4^{\gamma}$</td>
<td>$-0.0012, 0.0013$</td>
<td>$-0.0008, 0.0008$</td>
</tr>
</tbody>
</table>

The credibility limits of $|h_3^{Z\gamma}| < 0.027$ and $|h_4^{Z\gamma}| < 0.0013$ on the $CP$-conserving $Z\gamma$ couplings at $\Lambda = 1.2$ TeV and $|h_3^{Z\gamma}| < 0.022$ and $|h_4^{Z\gamma}| < 0.0009$ at $\Lambda = 1.5$ TeV; these are significantly tighter constraints on beyond-the-SM contributions than those provided by previously measured limits.

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium für Bildung und Forschung, Germany; the World Class University Program, the National Research Foundation of Korea; the Science and Technology Facilities Council and the Royal Society, U.K.; the Institut National de Physique Nucléaire et Physique des Particules/CNRS; the Russian Foundation for Basic Research; the Ministerio de Ciencia e Innovación, and Programa Consolider-Ingenio 2010, Spain; the Slovak R&D Agency; and the Academy of Finland.

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[13] The CDF detector can be described with a coordinate system consisting of $r$, the radial distance from the beam, $\phi$, the angle in azimuth, and $\theta$, the polar angle;
the origin is taken to be the geometric center of the
detector. The pseudorapidity $\eta$ is described as a function
of $\theta$: $\eta = -\ln(\tan(\frac{\theta}{2}))$. Transverse momentum and energy
are defined as $p_T = p \sin \theta$ and $E_T = E \sin \theta$, respectively.


[19] The additional energy in a cone of $\Delta R < 0.4$ must be less
than $0.1 \times E_T^\mu$ if $E_T^\mu < 20$ GeV and less than $2 + 0.02 \times
(E_T^\mu - 20)$ if $E_T^\mu > 20$ GeV for a photon to pass the iso-
lation selection.

[21] Missing $E_T (E_T^\mu)$ is defined by $E_T^\mu = -\sum_i E_T^i \hat{n}_i$, where $i$ is
the calorimeter tower number for $|\eta| < 3.6$, and $\hat{n}_i$ is a
unit vector perpendicular to the beam axis and pointing at
the $i$th tower. ($E_T = |E_T|$).
(1997).