$\mathcal{Z}\gamma$ production and limits on anomalous $ZZ\gamma$ and $Z\gamma\gamma$ couplings in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV


(The D0 Collaboration*)

1 Universität de Buenos Aires, Buenos Aires, Argentina
2 LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
3 Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
4 Universidade Federal do ABC, Santo André, Brazil
5 Instituto de Física Teórica, Universidade Estadual Paulista, São Paulo, Brazil
6 University of Science and Technology of China, Hefei, People's Republic of China
7 Universidad de los Andes, Bogotá, Colombia
8 Charles University, Faculty of Mathematics and Physics, Center for Particle Physics, Prague, Czech Republic
9 Czech Technical University in Prague, Prague, Czech Republic
10 Center for Particle Physics, Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
11 Universidad San Francisco de Quito, Quito, Ecuador
12 LPC, Université Blaise Pascal, CNRS/IN2P3, Clermont, France
13 LPSC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3, Institut National Polytechnique de Grenoble, Grenoble, France
14 CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
15 LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France
16 LPNHE, Universités Paris VI and VII, CNRS/IN2P3, Paris, France
17 CEA, Irfu, SPP, Saclay, France
18 IPHC, Université de Strasbourg, CNRS/IN2P3, Strasbourg, France
19 IPNL, Université Lyon 1, CNRS/IN2P3, Villeurbanne, France and Université de Lyon, Lyon, France
20 III. Physikalisches Institut A, RWTH Aachen University, Aachen, Germany
21 Physikalisches Institut, Universität Freiburg, Freiburg, Germany
22 II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
23 Institut für Physik, Universität Mainz, Mainz, Germany
24 Ludwig-Maximilians-Universität München, München, Germany
25 Fachbereich Physik, Bergische Universität Wuppertal, Wuppertal, Germany
26 Panjab University, Chandigarh, India
27 Delhi University, Delhi, India
28 Tata Institute of Fundamental Research, Mumbai, India
29 University College Dublin, Dublin, Ireland
30 Korea Detector Laboratory, Korea University, Seoul, Korea
31 CINVESTAV, Mexico City, Mexico
32 Nikhef, Science Park, Amsterdam, the Netherlands
33 Radboud University Nijmegen, Nijmegen, the Netherlands and Nikhef, Science Park, Amsterdam, the Netherlands
34 Joint Institute for Nuclear Research, Dubna, Russia
35 Institute for Theoretical and Experimental Physics, Moscow, Russia
36 Moscow State University, Moscow, Russia
37 Institute for High Energy Physics, Protvino, Russia
38 Petersburg Nuclear Physics Institute, St. Petersburg, Russia
39 Institució Catalana de Recerca i Estudis Avançats (ICREA) and Institut de Física d'Altes Energies (IFAE), Barcelona, Spain
40 Stockholm University, Stockholm and Uppsala University, Uppsala, Sweden
41 Lancaster University, Lancaster LA1 4YB, United Kingdom
42 Imperial College London, London SW7 2AZ, United Kingdom
43 The University of Manchester, Manchester M13 9PL, United Kingdom
44 University of Arizona, Tucson, Arizona 85721, USA
45 University of California Riverside, Riverside, California 92521, USA
46 Florida State University, Tallahassee, Florida 32306, USA
47 Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
48 University of Illinois at Chicago, Chicago, Illinois 60607, USA
We present a measurement of $p\bar{p} \rightarrow Z\gamma \rightarrow \ell^+\ell^−\gamma$ ($\ell = e, \mu$) production with a data sample corresponding to an integrated luminosity of 6.2 fb$^{-1}$ collected by the D0 detector at the Fermilab Tevatron $p\bar{p}$ Collider. The results of the electron and muon channels are combined, and we measure the total production cross section and the differential cross section $d\sigma/dp_T^\gamma$, where $p_T^\gamma$ is the momentum of the photon in the plane transverse to the beamline. The results obtained are consistent with the standard model predictions from next-to-leading order calculations. We use the transverse momentum spectrum of the photon to place limits on anomalous $ZZ\gamma$ and $Z\gamma\gamma$ couplings.

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INTRODUCTION

The standard model (SM) describes the electroweak interactions through a non-abelian gauge group $SU(2)_L \otimes U(1)_Y$, which includes self-interactions of gauge bosons. Because the $Z$ boson carries no electric charge, a coupling between a $Z$ boson and a photon is not permitted. The $Z\gamma$ production in the SM is dominated by the lowest-order Feynman diagrams shown in Fig. 1.

An excess in the number of high-energy photons can be a sign of new physics, e.g., supersymmetry, as described in Ref. 1 or new heavy fermions with nonstandard couplings to the gauge bosons, as discussed in Ref. 2. Such an excess of high-energy photons can be described by assuming only Lorentz and local $U(1)_{em}$ gauge invariant $ZZ\gamma$ and $Z\gamma\gamma$ trilinear gauge boson vertices of the form shown in Fig. 2 using an effective theory with eight complex coupling parameters, $h^i_Y$, where $i = 1, 2, 3, 4$ and $V = Z$ or $\gamma$. Here, the couplings parameters $h^i_Y$ and $h^i_Z$ ($h^i_Z$ and $h^i_Y$) are associated with dimension-six (dimension-eight) operators which allow for an interaction between a $Z$ boson and a photon. To conserve tree-level unitarity at asymptotically high energies, one can introduce form factors dependent on the square of the partonic center-of-mass energy, $\hat{s}$, given by $h^i_Y = h^i_Y / (1 + \hat{s} / \Lambda^2)^n$, where $\Lambda$ is the mass scale at which the new physics responsible for anomalous couplings is
introduced [3]. These anomalous gauge boson couplings would give rise to an excess of photons at high transverse momentum, $p_T^γ$, which can be searched for by measuring the total production cross section and the differential cross section $dσ/dp_T^γ$ for $Zγ → ℓ^+ℓ^−γ$ (ℓℓγ henceforth) production. If no evidence of new physics is seen, we can place limits on the real components of the CP-even coupling parameters, $h_{h3}^V$ and $h_{h4}^V$, for $Λ = 1.2$ and 1.5 TeV. Following Ref. [4], we choose form-factor powers for the production. If no evidence of new physics is seen, we can combine with a previous result in the same channels [3], along with another D0 result [6] that used 3.6 fb$^{-1}$ of $Zγ → ννγ$ production to place stringent limits on $Zγ$ anomalous couplings.

**FIG. 2:** Feynman diagrams illustrating anomalous $Zγ$ production with a $ZZγ$ vertex (a) and a $Zγγ$ vertex (b).

The D0 detector [11–18] consists of a central tracking system contained within 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, consisting of a silicon microstrip tracker (SMT) and a scintillating fiber tracker (CFT), provides coverage for charged particles in the pseudorapidity range $|η| ≤ 3$ [19]. 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 cryostat sector (CC) with coverage $|η| ≤ 1.1$ and two end calorimeters (EC) which extend coverage to $|η| ≈ 4.2$. The electromagnetic (EM) section of the calorimeter is segmented into four longitudinal layers (EM$i$, $i = 1$, 4) with transverse segmentation of $Δη × Δϕ = 0.1 × 0.1$, 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 a 1.8 T iron toroidal magnet, followed by two similar layers after the toroid. The coverage of the muon system corresponds to a pseudorapidity range $|η| < 2$.

**EVENT SELECTION**

Candidate $Zγ$ events are selected in the $e^+e^−γ$ and $μ^+μ^−γ$ ($eeγ$ and $μμγ$ henceforth) final states. The $p\bar{p}$ interaction vertex must be reconstructed within ±60 cm of the center of the D0 detector along the beam (z) axis. For the electron channel, a sample of candidate $Z$-boson events is collected with a suite of single-electron triggers. The electrons are selected by requiring an EM cluster in either the CC ($|η| < 1.1$) or EC ($1.5 < |η| < 2.5$) regions of the EM calorimeter with transverse momentum $p_T > 25$ (15) GeV/c for the electron candidate with the highest (next-to-highest) transverse energy contained within a cone of radius $ΔR = \sqrt{(Δη)^2 + (Δϕ)^2} = 0.2$, centered on the axis of the EM shower. At least 90%
of the cluster energy must be deposited within the EM section of the calorimeter. Electron candidates, with a shower shape consistent with that of an electron, are required to be spatially matched to a track and to be isolated in both the calorimeter and tracking detectors. To suppress jets and photons misidentified as electrons, a likelihood discriminant is built using a set of variables sensitive to differences in tracker activity and energy deposits in the calorimeter: the number of tracks and the scalar sum of the transverse momentum of all tracks within $\Delta R < 0.4$ of the EM cluster, the fraction of energy deposited in the EM section of the calorimeter, the longitudinal and transverse shower profile in the calorimeter, and the ratio between the transverse energy in the calorimeter and the transverse momentum of the electron associated track. To further suppress jets misidentified as electrons, in particular, for high instantaneous luminosity conditions, a neural network algorithm is trained on Drell-Yan $Z/\gamma^* \rightarrow e^+e^-$ and jet data, using information from the calorimeter and CPS: the numbers of cells above a threshold in EM1 within $\Delta R < 0.2$ and $0.2 < \Delta R < 0.4$ of the EM cluster, the number of CPS clusters within $\Delta R < 0.1$ of the EM cluster, and the squared-energy weighted width of the energy deposit in the CPS. Events where both electrons are contained within the EC are excluded because of the small signal acceptance. Candidate events where the Z boson decays into two muons are collected using a suite of single-muon triggers. Within the muon channel, muon candidates are required to be within $|\eta| < 2$ and matched to a well-isolated track in both the tracker and the calorimeter with transverse momentum $p_T > 15$ GeV/$c$. The highest $p_T$ muon must have $p_T > 20$ GeV/$c$. Both muon candidates are required to originate from within 2 cm of the interaction point in the $z$ direction.

Photon candidates in both the electron and muon channels are required to have transverse momentum $p_T^\gamma > 10$ GeV/$c$ within a cone of radius $\Delta R = 0.2$ centered around the EM shower in the CC. The rapidity of the photon, $\eta^\gamma$, is required to be $|\eta^\gamma| < 1.1$. Additionally, the photon candidate 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, $p_T^{\text{sum}}$, originating from the interaction point in an annulus of $0.05 < \Delta R < 0.4$ around the cluster is less than 2.0 GeV/$c$; (v) the EM cluster must not be spatially matched to either a reconstructed track or to energy depositions in the SMT or CFT detectors that are compatible with a trajectory of an electron [20]; and (vi) an output larger than 0.1 of an artificial neural network ($O_{NN}$) [21] 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.

The dilepton invariant mass, $M_{\ell\ell}$, is required to be greater than 60 GeV/$c^2$, and the photon must be separated from each lepton by $\Delta R_{\ell\gamma} > 0.7$. Additionally, each lepton must be separated from a jet by $\Delta R_{\ell j} > 0.5$. In the electron and muon channels, we select 1002 and 1000 data events, respectively. In order to reduce the contribution of final-state radiation (FSR), subset data samples are defined with the requirement that the reconstructed three-body invariant mass, $M_{\ell\ell\gamma}$, exceeds 110 GeV/$c^2$. With this additional requirement, 304 and 308 data events are selected in the electron and muon channels, respectively.

### Background subtraction

The selected sample is contaminated by a small admixture of $Z+$jet events in which a jet is misidentified as a photon. To estimate this background in the electron channel, the fraction of jets that pass the photon selection criteria but fail either the $p_T^{\text{sum}}$ or the shower width requirement, as determined by using a dijet data sample, is parametrized as a function of $p_T^\gamma$ and $\eta^\gamma$ (ratio method). The background from $Z+$jet production is then estimated starting from a data sample obtained by reversing the requirements either on $p_T^{\text{sum}}$ or on the shower width requirement, and applying the same parametrization. A systematic uncertainty associated with the estimation of the number of real photons in the data sample is due to the finite size of the dijet background sample. After subtracting the estimated background from the data in the electron channel, we estimate $926 \pm 53$ (stat.) $\pm 19$ (syst.) signal events when no $M_{\ell\ell}$ requirement is applied, and $255 \pm 15$ (stat.) $\pm 5$ (syst.) signal events with $M_{\ell\ell} > 110$ GeV/$c^2$.

To estimate the background in the muon channel, we use a matrix method to estimate the $Z+$jet background contribution. After applying all of the selection criteria described above, a tighter requirement on $O_{NN}$ is used to classify the data events into two categories, depending on whether the photon candidate passes ($p$) or fails ($f$) this requirement. The corresponding number of events compose a 2-component vector $(N_p, N_f)$. Thus, the sample composition is obtained by resolving a linear system of equations $(N_p, N_f)^T = E \times (N_{Z\gamma}, N_{Zj})^T$, where $N_{Z\gamma}$ (N_{Zj}) is the true number of $Z + \gamma$ ($Z+$jet) events in the fiducial region. The $2 \times 2$ efficiency matrix $E$ contains the photon $\varepsilon_{\gamma}$ and jet $\varepsilon_{\text{jet}}$ efficiencies that are estimated using photon and jet Monte Carlo (MC) samples and validated in data. Based on these studies, the efficiencies are parametrized as a function of the photon candidates’ $\eta^\gamma$ with 1.5% and 10% relative systematic uncertainties for $\varepsilon_{\gamma}$ and $\varepsilon_{\text{jet}}$, respectively. Having subtracted the esti-
mated background from data in the muon channel, we estimate 947 ± 40 (stat.) ± 16 (syst.) signal events when no $M_{\ell\ell}$ requirement is applied, and 285 ± 24 (stat.) ± 2 (syst.) signal events requiring $M_{\ell\ell\gamma} > 110 \text{ GeV}/c^2$.

As a cross-check, the $Z$+jet background is also estimated through a fit to the shape of the $O_{NN}$ distribution in data for both electron and muon channels, using MC templates constructed from simulated photon and jet events. The results are in good agreement with those obtained from the ratio and matrix methods.

RESULTS

Total cross section

The total cross section for $\ell\ell\gamma$ production is obtained from the ratio of the acceptance-corrected $\ell\ell\gamma$ rate for $M_{\ell\ell} > 60 \text{ GeV}/c^2$, $\Delta R_{\ell\ell} > 0.7$, $p_T^{\ell\ell} > 10 \text{ GeV}/c$, and $|\eta^{\gamma}| < 1$, to the total acceptance-corrected dilepton rate for $M_{\ell\ell} > 60 \text{ GeV}/c^2$. Henceforth, these acceptance requirements are referred to as the generator-level requirements. We utilize this method because uncertainties associated with the trigger efficiencies, reconstruction efficiencies, and integrated luminosity are larger than the theoretical uncertainties and cancel in the ratio. This ratio is multiplied by a theoretical estimate for the total cross section for inclusive $Z/\gamma^* \rightarrow \ell\ell$ production for $M_{\ell\ell} > 60 \text{ GeV}/c^2$:

$$\sigma_{Z\gamma} \times B = \frac{\kappa A_{\text{data}} (A \times \epsilon_{ID})_{\ell\ell\gamma}^{-1}}{N_{\text{data}} (A \times \epsilon_{ID})_{\ell\ell}} \times (\sigma_{Z\gamma} \times B)^{\text{NNLO}}_{\text{FEWZ}} \cdot (1)$$

Here, $N_{\text{data}}$ and $A_{\text{data}}$ are the number of measured $Z$ and background-subtracted $Z\gamma$ events in the data sample, respectively. The factor $(\sigma_{Z\gamma} \times B)^{\text{NNLO}}_{\text{FEWZ}}$ is calculated with the FEWZ next-to-next-to-leading-order (NNLO) generator [22]-[23], with the CTEQ6.6 parton distribution functions (PDF) [24]. The FEWZ theoretical prediction is 262.9 ± 8.0 pb, where the dominant uncertainty is from the choice of PDF. The term $B$ is the branching fraction for $Z/\gamma^* \rightarrow \ell\ell$, which in the SM is 3.4% for either electrons or muons. The factor $\kappa$ corrects for the resolution effects that would cause events not to pass the selections on the generator-level quantities, e.g., a generator-level photon with $p_T^{\gamma} < 10 \text{ GeV}/c$, but to pass the reconstruction requirements, e.g., a reconstructed photon with $p_T^{\gamma} > 10 \text{ GeV}/c$. This factor is only used for $Z \rightarrow \ell\ell\gamma$ events, and corrects for the photon energy smearing that dominates in the first $p_T^{\gamma}$ bin. The muon $p_T$ resolution affects both $Z/\gamma^* \rightarrow \ell\ell$ and $Z \rightarrow \ell\ell\ell$ and the corresponding correction cancel in the ratio of cross sections.

For the events that pass the generator-level requirements, the factors $(A \times \epsilon_{ID})_{\ell\ell\gamma}$ and $(A \times \epsilon_{ID})_{\ell\ell}$ provide the fraction of events that pass the analysis requirements, with all acceptances measured relative to the kinematic requirements at the generator level for the $\ell\ell$ and $\ell\ell\gamma$ final states, respectively. Events migrate between bins in $p_T^{\gamma}$ because of finite detector resolution, and these effects are taken into account in calculating $(A \times \epsilon_{ID})_{\ell\ell\gamma}$ as a function of $p_T^{\gamma}$, while $(A \times \epsilon_{ID})_{\ell\ell}$ is calculated for the entire $\ell\ell$ sample. To estimate $\kappa$ and $A \times \epsilon_{ID}$, we use inclusive $Z/\gamma^* \rightarrow \ell\ell$ events generated with the PYTHIA [25] generator with final-state radiation simulated using PHOTOS [26] and the CTEQ6.1L [27] PDF set. Because PYTHIA is a leading-order (LO) generator and does not reproduce the observed $p_T^{\gamma}$ spectrum in data, generated events are weighted to reflect the $p_T^{\gamma}$ distribution observed in Ref. [28]. Events are then traced through the D0 detector using a simulation based on GEANT [29].

Data events from random beam crossings are overlaid on the simulated interactions to reproduce the effects of multiple $pp$ interactions and detector noise. Simulated interactions that take into account the observed differences between data and simulation are reweighted, e.g., the $z$ coordinate of the vertex, instantaneous luminosity, trigger efficiency, lepton identification (ID) efficiency, photon ID efficiency, and resolution effects. Here, the factor $(A \times \epsilon_{ID})_{\ell\ell\gamma}$ has values of 0.15 (0.17) in the electron channel (muon channel). When no constraints on $M_{\ell\ell\gamma}$ are applied, the factor $\kappa$ has average values of $0.83 \pm 0.01$ (stat.) and $0.85 \pm 0.01$ (stat.) for the electron and muon channels, respectively, and the average value of $(A \times \epsilon_{ID})_{\ell\ell\gamma}$ is 0.12 for both the electron and muon channels. Values for $(A \times \epsilon_{ID})_{\ell\ell\gamma}$ and $\kappa$ are similar for the subsample requiring $M_{\ell\ell\gamma} > 110 \text{ GeV}/c^2$.

To account for systematic uncertainty on the migration into the sample from generated events with $p_T^{\gamma} < 10 \text{ GeV}/c$, we conservatively vary the number of events produced outside the generator-level requirements in the PYTHIA simulation by ±20%, found as an upper estimate in studies of photon energy resolution in this kinematic regime, to measure the effect on the final cross section measurement. We find that the effect introduces a 1.5% systematic uncertainty on the total cross section. The dominant uncertainty corresponding to the calculation of $A \times \epsilon_{ID}$ is due to choice of the PDF set. There are 20 free parameters in the CTEQ6.1L parametrization of the PDF that reflect fits to data from previous experiments. The uncertainties on acceptance and efficiencies due to the PDF parametrization are estimated using the CTEQ6.1M PDF uncertainties, following Ref. [30]. We find a total PDF uncertainty of 3.5%, dominated by the uncertainty on the acceptance-correction to the full geometrical lepton acceptance. The photon ID efficiency is determined from a simulated sample of photons and is estimated to have an uncertainty of 10% for $p_T^{\gamma} < 15 \text{ GeV}/c$ and 3% for $p_T^{\gamma} > 15 \text{ GeV}/c$.

To reduce the contribution of FSR in the data samples, we calculate the cross section with and without the $M_{\ell\ell\gamma} > 110 \text{ GeV}/c^2$ requirement. To combine the
electron and muon channels, we utilize the method in Ref. [31], which averages the results of measurements with correlated systematic uncertainties. We assume the PDF and photon ID efficiency uncertainties to be 100% correlated between the two channels. The total cross section results can be found in Tables III and IV. The measurements are consistent with the NLO MCFM [32] prediction using CTEQ6.6 PDF set [24] and the renormalization and factorization scales evaluated at the mass of the W boson, $M_W = 80 \text{ GeV}/c^2$. The PDF uncertainties associated with the SM prediction are evaluated following Ref. [30]. We reevaluate the values for the $p_T$ spectrum calculated by NLO MCFM with the renormalization and factorization scales set to 160 GeV/$c^2$ and again at 40 GeV/$c^2$ and use these as estimates of the theoretical uncertainty of 1 standard deviation relative to the central NLO MCFM value.

TABLE I: Summary of the total cross-section measurements, when no $M_{ll\gamma}$ requirement is applied, for individual channels, combined channels, and the NLO MCFM calculation with associated PDF and scale uncertainties. 

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\sigma_{Z\gamma} \times B$ [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ee\gamma$ data</td>
<td>$1026 \pm 62$ (stat.) $\pm 60$ (syst.)</td>
</tr>
<tr>
<td>$\mu\mu\gamma$ data</td>
<td>$1158 \pm 53$ (stat.) $\pm 70$ (syst.)</td>
</tr>
<tr>
<td>$ll\gamma$ combined data</td>
<td>$1089 \pm 40$ (stat.) $\pm 65$ (syst.)</td>
</tr>
<tr>
<td>NLO MCFM</td>
<td>$1096 \pm 34$ (PDF) $\pm 4$ (scale)</td>
</tr>
</tbody>
</table>

TABLE II: Summary of the total cross-section measurements, with the $M_{ll\gamma} > 110 \text{ GeV}/c^2$ requirement, for individual channels, combined channels, and the NLO MCFM calculation with associated PDF and scale uncertainties. 

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\sigma_{Z\gamma} \times B$ [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ee\gamma$ data</td>
<td>$281 \pm 17$ (stat.) $\pm 11$ (syst.)</td>
</tr>
<tr>
<td>$\mu\mu\gamma$ data</td>
<td>$306 \pm 28$ (stat.) $\pm 11$ (syst.)</td>
</tr>
<tr>
<td>$ll\gamma$ combined data</td>
<td>$288 \pm 15$ (stat.) $\pm 11$ (syst.)</td>
</tr>
<tr>
<td>NLO MCFM</td>
<td>$294 \pm 10$ (PDF) $\pm 2$ (scale)</td>
</tr>
</tbody>
</table>

**Differential cross section $d\sigma/dp_T^\gamma$**

We use the matrix inversion technique [33] to unfold the experimental resolution and extract $d(\sigma_{Z\gamma} \times B)/dp_T^\gamma$, ($d\sigma/dp_T^\gamma$, henceforth), the differential cross section for $Z\gamma \rightarrow ll\gamma$, as a function of the true $p_T^\gamma$. The elements of the smearing matrix between true and reconstructed $p_T^\gamma$ bins are estimated using the full simulation of the detector response on a sample of $Z\gamma$ events generated using PYTHIA. Then, the matrix is inverted to obtain the unsmeared spectrum. We confirm that the unfolding procedure introduces a negligible bias. Following Ref. [34], the position of the data points are plotted in Figs. 3 and 4 at the value of $p_T^\gamma$ where the cross section equals the average value for that bin. The theoretical uncertainties associated with the choice of PDF and the renormalization and factorization scales are determined analogously to the theoretical prediction for the total production cross section. The combined differential cross sections $d\sigma/dp_T^\gamma$ are shown in Figs. 3 and 4 for no $M_{ll\gamma}$ requirement and $M_{ll\gamma} > 110 \text{ GeV}/c^2$, respectively. The values associated with Figs. 3 and 4 are given in Tables III and IV.

**LIMITS ON ANOMALOUS COUPLINGS**

To set limits on anomalous trilinear gauge boson couplings, we generate $Z\gamma$ events for different values of the anomalous couplings using the NLO Monte Carlo generator of Ref. [3]. SM Drell-Yan production is included by reweighting the $p_T^\gamma$ spectrum to MCFM for very small anomalous couplings. As shown in Fig. 5, anomalous $Z\gamma$ couplings would contribute to an excess of high-energy photons as compared to the SM prediction. We apply the following generator-level requirements: $M_{ll\gamma} > 60 \text{ GeV}/c^2$, $\Delta R_{ll\gamma} > 0.7$, $p_T^\gamma > 10 \text{ GeV}/c$, $|\eta| < 1$, and $M_{ll\gamma} > 110 \text{ GeV}/c^2$, generate $p_T^\gamma$ templates as a function of the anomalous couplings, and use the known acceptance and resolution functions to fold the predicted generator-level distribution into a reconstruction-level distribution for $p_T^\gamma$. Using Poisson statistics for $p_T^\gamma > 30 \text{ GeV}/c$, we define a likelihood function to com-
TABLE IV: Summary of the unfolded differential cross section $d\sigma/dp_T^{\gamma}$, when no $M_{\ell\ell\gamma}$ requirement is applied, and NLO mcfm predictions with PDF and scale uncertainties.

<table>
<thead>
<tr>
<th>$p_T^{\gamma}$ bin [GeV/c]</th>
<th>$p_T^{\gamma}$ center [GeV/c]</th>
<th>$d\sigma/dp_T^{\gamma}$ [fb/(GeV/c)]</th>
<th>$\ell\ell\gamma$ combined data</th>
<th>NLO mcfm</th>
</tr>
</thead>
<tbody>
<tr>
<td>10–15</td>
<td>12.4</td>
<td>111.14 ± 4.40 (stat.) ± 11.99 (syst.)</td>
<td>104.02 ± 4.10 (PDF) ± 1.58 (scale)</td>
<td></td>
</tr>
<tr>
<td>15–20</td>
<td>17.2</td>
<td>51.41 ± 3.83 (stat.) ± 2.65 (syst.)</td>
<td>57.13 ± 2.23 (PDF) ± 1.11 (scale)</td>
<td></td>
</tr>
<tr>
<td>20–25</td>
<td>22.5</td>
<td>25.34 ± 2.74 (stat.) ± 1.13 (syst.)</td>
<td>28.77 ± 0.43 (PDF) ± 1.7 (scale)</td>
<td></td>
</tr>
<tr>
<td>25–30</td>
<td>27.5</td>
<td>8.03 ± 1.45 (stat.) ± 0.40 (syst.)</td>
<td>10.16 ± 0.26 (PDF) ± 0.7 (scale)</td>
<td></td>
</tr>
<tr>
<td>30–40</td>
<td>34.4</td>
<td>3.23 ± 0.60 (stat.) ± 0.17 (syst.)</td>
<td>4.15 ± 0.16 (PDF) ± 0.34 (scale)</td>
<td></td>
</tr>
<tr>
<td>40–60</td>
<td>48.5</td>
<td>1.70 ± 0.26 (stat.) ± 0.088 (syst.)</td>
<td>1.60 ± 0.061 (PDF) ± 0.083 (scale)</td>
<td></td>
</tr>
<tr>
<td>60–100</td>
<td>76.5</td>
<td>0.34 ± 0.079 (stat.) ± 0.018 (syst.)</td>
<td>0.42 ± 0.017 (PDF) ± 0.028 (scale)</td>
<td></td>
</tr>
<tr>
<td>100–200</td>
<td>124.5</td>
<td>0.038 ± 0.014 (stat.) ± 0.002 (syst.)</td>
<td>0.052 ± 0.001 (PDF) ± 0.001 (scale)</td>
<td></td>
</tr>
</tbody>
</table>

FIG. 4: Unfolded $d\sigma/dp_T^{\gamma}$ distribution with $M_{\ell\ell\gamma} > 110$ GeV/c$^2$ for combined electron and muon data compared with the NLO mcfm prediction.

TABLE V: Summary of the 1D limits on the $Z\gamma$ and $Z\gamma\gamma$ coupling parameters at the 95% C.L.

<table>
<thead>
<tr>
<th>$\Gamma_{\ell\ell\gamma}$</th>
<th>$h_{03}$</th>
<th>$h_{04}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L = 1.2$ TeV</td>
<td>0.050</td>
<td>0.0033</td>
</tr>
<tr>
<td>$L = 1.5$ TeV</td>
<td>0.026</td>
<td>0.0013</td>
</tr>
<tr>
<td>$\nu\nu\gamma$</td>
<td>0.052</td>
<td>0.0034</td>
</tr>
<tr>
<td>$L = 1.5$ TeV</td>
<td>0.027</td>
<td>0.0043</td>
</tr>
</tbody>
</table>

pare the combined electron and muon channels with a predicted distribution for given values of anomalous couplings. In the absence of any significant deviation from the SM prediction, we set one-dimensional (1D) and two-dimensional (2D) limits on the anomalous coupling parameter values at the 95% C.L. A combined log-likelihood function using all data is defined by the sum of the individual log-likelihood functions of the electron and muon channels. We include the effect of systematic uncertainties associated with transforming a Monte Carlo $p_T^{\gamma}$ template from the generator-level into a reconstructed distribution and find that these uncertainties contribute to the value of the calculated limits on the order of 1%. We generate a 10 × 10 grid of templates for the $p_T^{\gamma}$ distri-
tions for $Z\gamma$ are consistent with the SM at NLO predicted by $d\sigma/dp_\gamma$. The 1D and 2D limits on the anomalous coupling parameters are shown in Figs. 6 and 7 utilizing the electron and muon channels. In these figures, the dotted lines represent the theoretical limits on the anomalous coupling values, beyond which $S$-matrix unitarity is violated. Because the $h_{04}$ parameters come from dimension-eight operators, the limits are more constrained than those of $h_{03}$ couplings, which are dimension-six.

We combine these results with those of a previous D0 $Z\gamma$ analysis [6]. In that analysis, the 1D and 2D limits on the anomalous couplings parameter were calculated using a data sample corresponding to an integrated luminosity of 1 fb$^{-1}$ of data collected between October 2002 and February 2006 (3.6 fb$^{-1}$ of data collected between October 2002 and September 2008) in the $ee\gamma$ and $\mu\mu\gamma$ channels ($\nu\nu\gamma$ channel), for $\Lambda = 1.5$ TeV. Results can be found in Fig. 8 and Table V.

**CONCLUSIONS**

We have measured the differential and total cross sections for $Z\gamma \rightarrow \ell\ell\gamma$ production in $p\bar{p}$ collisions using the D0 detector at the Tevatron Collider with and without a $M_{\ell\ell\gamma} > 110$ GeV/c$^2$ requirement. Both the total production cross sections and differential cross sections $d\sigma/dp_\gamma$, are consistent with the SM at NLO predicted by MCFM.
FIG. 7: The 2D (contour) and 1D (cross) limits on the anomalous parameters for (a) $ZZ\gamma$ and (b) $Z\gamma\gamma$ vertices at the 95\% C.L. for $\Lambda = 1.5$ TeV. Limits on $S$-matrix unitarity are represented by the dotted lines.

FIG. 8: The 2D (contour) and 1D (cross) limits on coupling parameters for (a) $ZZ\gamma$ and (b) $Z\gamma\gamma$ vertices at the 95\% C.L. for $\Lambda = 1.5$ TeV. Limits on $S$-matrix unitarity are represented by the dotted lines.

Pseudorapidity is defined as $\eta = -\ln[\tan(\theta/2)]$, 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.