DØNote 5156-CONF

Study of $Z(\gamma) \to ee\gamma$ events in DØ Run II p17 Data

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We present a measurement of the $Z\gamma$ production cross section. The measurement is based on 387 candidates in the $ee\gamma$ final state using 1026 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV.

I. INTRODUCTION

Studies of events containing pairs of vector bosons provide important tests of the standard model (SM) of electroweak interactions. In the SM, the trilinear gauge couplings of the Z boson to the photon are zero; therefore, photons do not interact with Z bosons at lowest order. Evidence for such an interaction would indicate new physics [1].

We present a new study of $Z\gamma$ production in $p\bar{p}$ collisions using Z boson decays to e^+e^-, where the dilepton system can be produced by either an on-shell Z boson, or a virtual Z boson or γ (the Drell-Yan process). The dilepton plus photon final state, $\ell^+\ell^-\gamma$, can be produced in the SM through either of two processes. The photon may be emitted through initial state radiation (ISR) from one of the partons in the p or $\bar{p}$, or produced as final state radiation (FSR) from one of the final state leptons. We collectively refer to these processes as $Z\gamma$ production.

The SM $Z\gamma$ processes produce photons with a rapidly falling transverse energy, E_T^γ. In contrast, anomalous $ZZ\gamma$ and $Z\gamma\gamma$ couplings, which appear in extensions of the SM, can cause production of photons with high E_T^γ and can increase the $\ell^+\ell^-\gamma$ cross section compared to the SM prediction. Below we describe a search for this anomalous production within the framework of Ref. [2]. This formalism assumes only that the $ZV\gamma$ (V=Z, γ) couplings are Lorentz- and gauge-invariant. The most general $ZV\gamma$ coupling is parameterized by two CP-violating (h_1^V and h_2^V) and two CP-conserving (h_3^V and h_4^V) complex coupling parameters. Partial wave unitarity is ensured at high energies by using a form-factor ansatz $h_i^V = h_{i0}^V/(1+\hat{s}/\Lambda^2)^{n_i}$ ($i = 1, ..., 4$), where $\sqrt{\hat{s}}$ is the parton center-of-mass energy, Λ is the form-factor scale, and n_i is the form factor power. We set the form factor powers $n_1 = n_3 = 3$ and $n_2 = n_4 = 4$, in accordance with Ref. [2].

Previous studies of Z boson and photon production have been made by the CDF [3] and DØ [4, 5] collaborations using $p\bar{p}$ collisions, and by the DELPHI [6], L3 [7], and OPAL [8] collaborations using e^+e^- collisions. The combined LEP results are available in Ref. [9].

II. DØDETECTOR AND DATA SAMPLE

The data for this analysis were collected by the DØ Run II detector at the Fermilab Tevatron Collider with $p\bar{p}$ center-of-mass energy $\sqrt{s} = 1.96$ TeV between October 2002 and December 2005. The integrated luminosity used for this analysis is 1026 pb^{-1} for the electron final state.

The DØ detector [10] consists of an inner tracker, surrounded by liquid-argon/uranium calorimeters, and a muon spectrometer. The detector sub-systems provide measurements over the full range of azimuthal angle ϕ [11] and over different, overlapping regions of detector pseudorapidity η. The inner tracker consists of a silicon microstrip tracker (SMT) and a central fiber tracker (CFT), both located within a 2 T superconducting solenoidal magnet. The CFT and the SMT have coverage out to $|\eta| \lesssim 1.8$ and $|\eta| \approx 3.0$, respectively. The calorimeter is divided into a central calorimeter (CC) covering the range $|\eta| < 1.1$ and two end calorimeters (EC) housed in separate cryostats which extend coverage to $|\eta| \approx 4$. The calorimeters are longitudinally segmented into electromagnetic (EM) and hadronic sections. The muon system lies outside the calorimeters and consists of tracking detectors, scintillation trigger counters, and a 1.8 T toroid magnet. It has coverage up to $|\eta| \approx 2.0$. Luminosity is measured using plastic scintillator arrays located in front of the EC cryostats, covering $2.7 < |\eta| < 4.4$.

III. EVENTS SELECTION AND PARTICLE IDENTIFICATION

The data were collected with a three-level trigger system (L1, L2, and L3). We require that the events in the electron decay channel satisfy one of the high-E_T single electron triggers. At L1 the single electron triggers select events based on the energy deposited in the EM section of the calorimeter; typical L1 requirements are greater than 10-15 GeV. At L3, additional requirements are imposed on the fraction of energy deposited in the EM calorimeter and the shape of the energy deposition. The efficiency of the electron trigger requirement is about 99%. Electrons are reconstructed as clusters of energy in the calorimeter. These clusters are required to have 90% of their energy deposited in the EM calorimeter (in either the central calorimeter $|\eta| < 1.1$, or the end calorimeter $1.5 < |\eta| < 2.5$). We require that the longitudinal and transverse shower shape of the cluster is consistent with that expected from an electron, and that the cluster is isolated from other activity in the calorimeter. Electron candidates in the central and end calorimeters are required to have spatially matched tracks. At least one electron candidate must be identified in the CC region and at least one is required to have $p_T > 25$ GeV/c. Due to different acceptances and efficiencies in the CC and EC regions we divide the analysis of the electron channel into two parts: data with both electrons identified in the central region (CC-CC), and the data with one electron in the central region, and the other in the endcap (CC-EC).

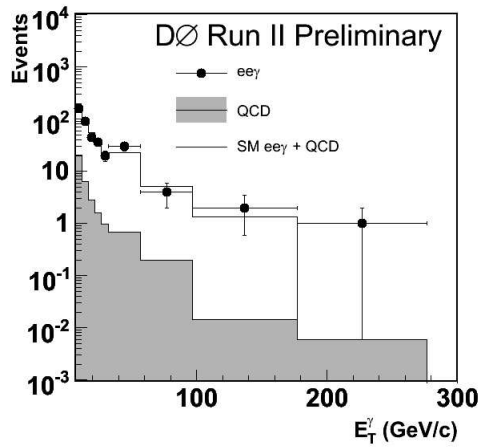

FIG. 1: Photon candidate E_T spectrum for $ee\gamma$ data (solid circles), QCD background (shaded histogram), the Monte Carlo simulation of the $ee\gamma$ production with the standard model plus background (solid histogram). The Monte Carlo distribution is normalized to the luminosity.

Z boson candidates are reconstructed by requiring a pair of high-p_T ($p_T > 15$ GeV/c) electrons that form an invariant mass above 30 GeV/c^2.

In addition to a Z boson candidate, we require events to have a photon candidate, with a separation from both leptons of $\Delta\mathcal{R} = \sqrt{(\phi_e - \phi_\gamma)^2 + (\eta_e - \eta_\gamma)^2} > 0.7$ and with $E_T^\gamma > 7$ GeV. Photons are reconstructed as energy clusters in the central calorimeter. The transverse shower shape of the cluster must be consistent with that expected from a photon. We also require a photon candidate to deposit at least 96% of its energy in the EM calorimeter and to be isolated from other activity in the calorimeter and the tracker.

Electron detection efficiencies for the above requirements are determined using a sample of $Z \to ee$ candidates. The combined trigger and reconstruction efficiency is measured to be $(72.3 \pm 2.1)\%$ for the CC-CC topology and $(54.7 \pm 3.0)\%$ for the CC-EC topology. The uncertainty is mostly due to electron identification uncertainty. The photon identification efficiency is measured as a function of E_T^γ using a Monte Carlo simulation. The photon identification efficiency is E_T-dependent and rises from about 53% at 7 GeV to about 95% above 75 GeV.

Background from processes with photons and leptons from misidentified jets is found to be negligible. The only significant source of background to $Z\gamma$ production is from Z+jets processes in which a jet is misidentified as a photon. We measure a rate at which em-like jet passes the photon identification criteria. We use eventsthat satisfied jet trigger requirements and with a high-quality jet reconstructed and matched to the trigger object. Then the E_T-dependent fake rate is defined as a ratio of transverse momenta for all photon candidates in these events that satisfied the photon identification criteria normalized by the transverse momenta of all EM candidates that are just reconstructed with SCone method (id -11, 10, and 11) and that are in the geometrical acceptance. The misidentification probability is about 0.11 and decreases with E_T. We further take out the contribution from real photons contaminating the jet-enriched sample in the high-E_T region according to [12]. To estimate Z+jet background we use the transverse momenta of the photon candidates in the sample of Z bosons reconstructed with SCone EM object (id -11, 10, and 11) that is in the geometrical acceptance defined for the photon candidates. We will refer to this distribution to as $dN/p_T[Z + em]$. We also use a p_T distribution of th ephotons in the final $Z(\gamma)$ sample which we denote as $dN/p_T[final]$. Number of background events is then evaluated to the formula:

$$N_{QCD} = f_{QCD}\ N/p_T[Z + jet] = f_{QCD}(\epsilon_\gamma - f_{QCD})^{-1}(\epsilon_\gamma dN/p_T[Z + em] - dN/p_T[final]) \quad (1)$$

In this equation ϵ_γ and f_{QCD} are the E_T-dependent photon identification efficiency and photon misidentification rate respectively. We obtain $18.3 \pm 3.0(stat.) \pm 2.9(syst.)$ QCD background events for the CC-CC topology and $14.8 \pm 2.5(stat.) \pm 2.2(syst.)$ for the CC-EC topology.

IV. MONTE CARLO SAMPLE

We use an event generator employing leading order (LO) QCD calculations and first order EW radiation with a detector simulation tuned with Z boson candidates to calculate the acceptances for the data and expected rates from both the SM and anomalous $Z\gamma$ production [2]. We use the CTEQ6L [14] parton distribution function (PDF) set. We

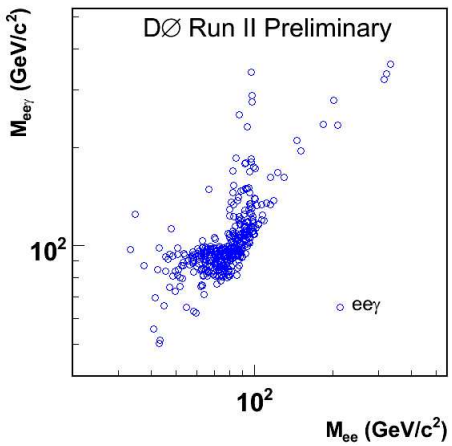

FIG. 2: Di-electron+photon *vs.* di-electron mass of $Z\gamma$ candidates.

estimate the uncertainty due to the PDF choice to be 3.3% using the prescription in Ref. [15]. The overall efficiency of the event selection criteria to reconstruct $Z(\gamma) \to ee\gamma$ is calculated to be 0.053 ± 0.003 for the CC-CC topology and 0.023 ± 0.002 for the CC-EC topology. Using a NLO $Z\gamma$ Monte Carlo [16] generator, we calculate an E_T^γ-dependent k-factor for each point in the anonalous coupling grid to properly simulate NLO effects for the anomalous coupling LO Monte Carlo samples.

V. SELECTED DATA AND $Z(\gamma)$ CROSS-SECTION MEASUREMENT

We observe 387 events in the electron channel, to be compared to the SM estimate of 327.3 $ee\gamma$ events and 33.1 ± 6.4 background events. The uncertainty in the background estimation is dominated by the uncertainty in the jet misidentification probability.

The E_T spectrum for photon candidates is shown in Fig. 1 with the estimation of the total SM prediction and its QCD background component overlaid. The highest photon transverse energy is 262 GeV. In Fig. 2 we plot the three-body mass ($M_{ee\gamma}$) against the di-electron mass (M_{ee}) for each event in the data. The di-electron and three-body mass distributions are given in Fig. 3. The ISR events with a dilepton system produced by an on-shell Z boson populate a vertical band at M_{ee} around Z boson mass, M_Z, and $M_{ee\gamma} > M_Z$. The on-shell Z boson FSR events cluster along a horizontal band at $M_{ee\gamma} = M_Z$ and have $M_{ee} < M_Z$. The Drell-Yan events populate the diagonal band with $M_{ee} \approx M_{ee\gamma}$ extending from the lower left to the upper right corner of the plot.

For events satisfying the phase space requirements; $\Delta\mathcal{R}_{e\gamma} > 0.7$, $E_T^\gamma > 7$ GeV, and $M_{ee} > 30$ GeV/c^2, the combined cross section times branching ratio is measured to be 4.51 ± 0.37 (stat+sys)± 0.27 (lum) pb, where the first uncertainty includes contributions from statistics and all systematic effects except the luminosity, and the second is due to the luminosity measurement uncertainty [18]. This value is in agreement with the expected value of 4.2 ± 0.2 pb from NLO theory calculations [16].

VI. CONCLUSION

We have studied a sample of 387 $ee\gamma$ events, consistent with $Z\gamma$ production. The $ee\gamma$ cross section is measured to be 4.51 ± 0.37(stat+syst) $\pm$ 0.27(lum) pb. This value is consistent with the SM expectations. We observe no significant deviation from the SM expectation in the total cross-section or photon E_T distribution.

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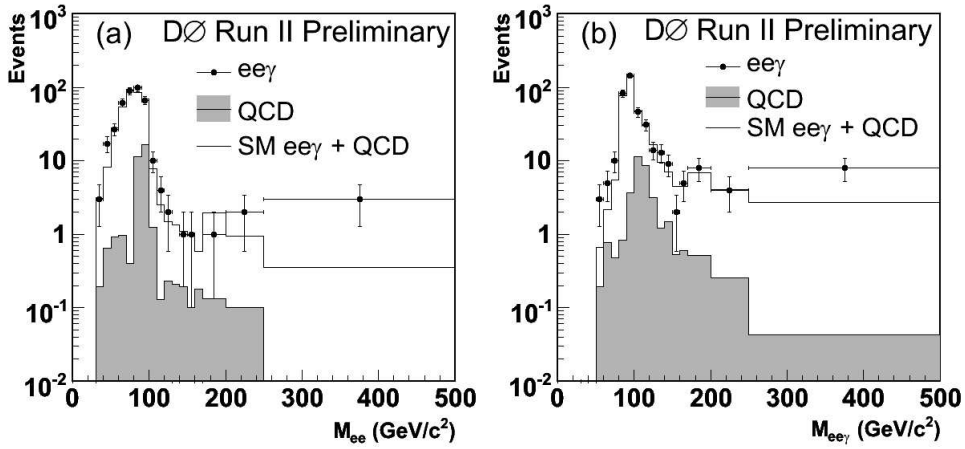

FIG. 3: (a) Di-electron mass and (b) di-electron+photon mass of $ee\gamma$ data (solid circles), QCD background (shaded histogram), and the standard model plus background (histogram). The Monte Carlo distribution is normalized to the luminosity.

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