DØnote 4488

Measurement of the cross-section for $Z(\gamma) \to \ell\ell\gamma + X$ in DØ Run II Data.

The DØ Collaboration
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In this note we present a measurement of the cross-section for $Z(\gamma) \to \ell\ell\gamma + X$ process for the transverse energy of a photon candidate $\mathrm{E}_T(\gamma) > 8$ GeV, a separation between a photon and leptons from Z decay $\Delta R_{\ell\gamma} > 0.7$, and invariant mass of di-lepton pair $M_{\ell\ell} > 30$ GeV/c^2. Using 177 pb^{-1} of data for the electron channel and 144 pb^{-1} for the muon channel we observed 33 and 68 events with background estimated to be 4.7 ± 0.7 and 10.1 ± 1.3 events, respectively. The measured value for the cross-section with both channels combined is $3.86 \pm 0.46(\mathrm{stat.} + \mathrm{syst.}) \pm 0.25(\mathrm{lumi.})$ pb. This agrees with a theory prediction of 4.3 pb.

Preliminary Results for Summer 2004 Conferences

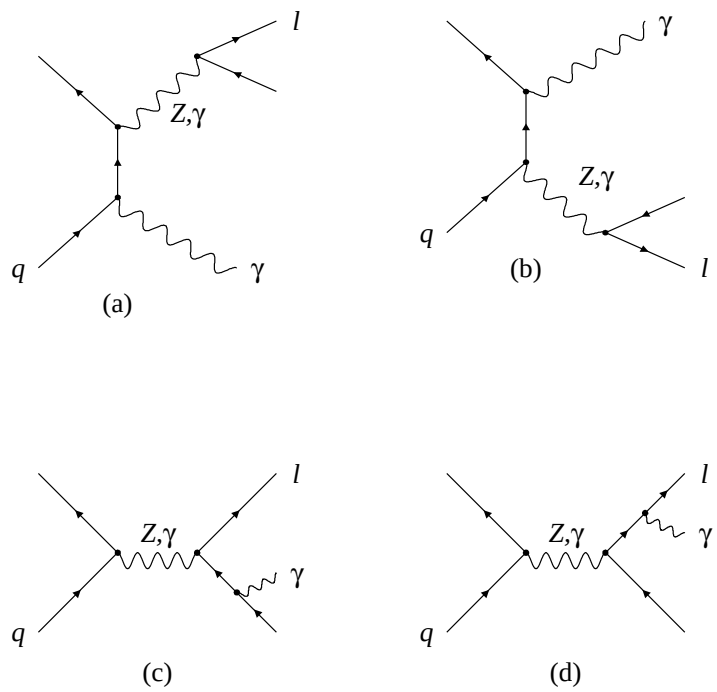

FIG. 1: Standard Model Feynman diagrams describing $Z(\gamma) \to \ell\ell\gamma$ production: (a) and (b) describe initial state radiation; (c) and (d) describe final state radiation.

I. INTRODUCTION

The Standard Model of electroweak interactions is described by the non-abelian gauge group $SU(2)_L \times U(1)_Y$. The symmetry transformations of the group permits gauge bosons (Z, W, and γ) to self-interact via trilinear gauge boson vertexes. The cross-sections of such processes are quite small within the Standard Model (SM). However, a presence of non-SM (anomalous) couplings at the trilinear gauge boson vertexes increases the cross-section, especially at higher values of the boson's transverse momentum (p_T). Observation of anomalously high gauge boson production would indicate new physics. Thus, a measurement of the di-boson cross-section and measurement of the trilinear gauge boson couplings are important tests of the SM. This analysis concentrates on measurement of the $Z(\gamma) \to \ell\ell\gamma$ cross-section. It is a stepping-stone for the detailed analysis of the $Z(\gamma) \to \ell\ell\gamma$ production, such as measurement of $Z\gamma^*\gamma$ and $ZZ^*\gamma$ trilinear couplings which are predicted to be zero in the SM (see Fig. 1).

II. DATA

The analysis described in the note is performed on the data collected by the DØ detector [1] between August 2002 and September 2003. We used only the data which were collected during period of good performance of both calorimeter and the central tracking systems. In addition, we require the performance of muon reconstruction system to be satisfactory for the $Z(\gamma) \to \mu\mu\gamma$ analysis. Overall integrated luminosity of the datasets for the study of electron and muon Z decay production is 177 pb^{-1} and 144 pb^{-1}, respectively.

III. DATA SELECTION

To reconstruct $Z(\gamma) \to \ell\ell\gamma$ production in the data we need to identify a photon and two leptons (a pair of muons or electrons) that are consistent with being produced from Z decay. Muons are identified by a high transverse momentum track in the muon spectrometer that matches spatially with a central track of $p_T > 15$ GeV/c. The muon candidates must be in the geometrical acceptance of the muon spectrometer. This requirement excludes muons that are close to beam-pipe (pseudorapidity $|\eta| > 2$), and it excludes muons in the bottom gap defined by azimuth angle ϕ between 4.15 and 5.15 rad and $|\eta| < 1.25$. Muon candidates are required to be isolated both in the central tracker and in the calorimeter to reduce background from jets with soft muons, *e.g.*, b-quark jets.

Electrons and photons are first identified as electromagnetic (EM) clusters found in the central ($|\eta| < 1.05$) or end calorimeters ($1.5 < |\eta| < 2.3$) using a simple cone algorithm. The fraction of energy in the EM calorimeter within the cone is required to be greater than 0.9. The EM cluster is further required to be energetically isolated from other calorimeter clusters. Electron candidate is an EM object that have a spatially matched track with a momentum that is consistent with the energy of EM cluster. Shower shape requirements further reduce the contamination from hadronic jets reconstructed as EM clusters.

Photons are reconstructed as EM clusters found in the central calorimeter that are not spatially matched with any of the tracks reconstructed by the tracking system. We require the sum of the p_T of tracks within a hollow cone of size $0.05 < \Delta R < 0.4$ to be less than 2 GeV/c. We require the shower width of the photon candidate to be less than 3.7 cm to reduce the background from jets identified as EM clusters. The photon transverse energy E_T is required to exceed 8 GeV. The photon candidate is further required to be separated from both of the lepton candidates by $\Delta R_{\ell\gamma} > 0.7$.

To select $Z \to ee$ decay candidates we require the event to have a pair of electrons, one with $p_T > 15$ GeV/c, and the other with $p_T > 25$ GeV/c. We require one of the electron candidates to be in the central calorimeter. In addition, we require the invariant mass of the two electrons to be greater than 30 GeV/c^2. These selection criteria yield 6,970 $Z \to$ee candidate events. $Z \to \mu\mu$ decay candidates are selected by a requiring the event to have two muon candidates that are not spatially collinear by at least 0.05 rad to reduce contamination from a cosmic muon reconstructed as two muons. The invariant mass of the two muons must exceed 30 GeV/c^2. After the selection criteria are applied, we observed 14,131 $Z \to \mu\mu$ candidate events.

After requiring events to have at least one photon candidate we observed 33 events in the $Z(\gamma) \to ee\gamma$ channel and 68 events in the $Z(\gamma) \to \mu\mu\gamma$ channel.

IV. MEASUREMENT OF GEOMETRIC ACCEPTANCE, KINEMATIC, TRIGGER, AND OFFLINE IDENTIFICATION EFFICIENCIES

The geometric acceptance and the efficiency of the kinematic criteria are studied using an event generator [2, 3] referred-to as the "Baur Monte Carlo". This is a leading-order QCD Monte Carlo where the $Z\gamma$ system is produced with no transverse momentum. To simulate the effects of higher-order QCD diagrams such as gluon radiation, the $Z\gamma$ was given a transverse momentum boost according to Pythia [4] simulation using CTEQ5L [5] parton distribution functions. We measure the geometric acceptance and efficiency of kinematic requirements to be 0.096 ± 0.002 and 0.178 ± 0.002 for the electron and the muon channels, respectively.

The efficiencies of trigger and offline identification requirements are measured by analyzing $Z \to \ell\ell$ decays, where only one of the leptons is required to satisfy strict identification requirements. The other lepton candidate is unbiased with respect to the selection criteria and is used to measure the efficiencies of trigger and offline identification requirements. We measure these efficiencies to be 0.51 ± 0.02 and 0.72 ± 0.01 for the electron and the muon channels.

The efficiency of photon-specific requirements is calculated using electrons produced by Z, J/Ψ, and Υ decays and corrected by Monte Carlo simulation of electron and photon shower difference. The results are further confirmed by simultaneous fit of two data samples, one that contained $\mathrm{W}\gamma \to \mu\nu\gamma$ candidates plus background events and a second sample that contained only background events. The photon reconstruction efficiency is measured to be 0.82 ± 0.02.

The overall selection criteria efficiency for the electron channel is measured to be 0.040 ± 0.003, and that for the muon channel is 0.106 ± 0.003.

V. BACKGROUND ESTIMATES

The main background to $Z\gamma$ processes is Z+jet production, where the jet is misidentified as a photon. The contribution from this background is estimated by measuring a probability P for which a jet is reconstructed as a photon from data. It is found that the value of P depends on the jet transverse energy E_T and ranges from 0.0044

TABLE I: Summary of the components to the calculation of the cross-section.

Parameter	electron channel	Muon channel
N_{cand}	33.0 ± 5.7 events	68.0 ± 8.3 events
N_{bkg}	4.7 ± 0.7 events	10.1 ± 1.3 events
$\epsilon_{ll\gamma}$	0.040 ± 0.003	0.106 ± 0.003
$\int \mathcal{L}dt$	177 ± 12 pb^{-1}	144 ± 9 pb^{-1}

for jets with $E_T = 10$ GeV to 0.0020 for jets with $E_T = 50$ GeV. This probability is folded with the number of jets in Z+jet events in the two decay channels. The uncertainty in this background is given by the uncertainty for a jet to be misreconstruced as a photon. For the electron channel the Z+jet background is 4.5 ± 0.7. That for the muon channel is measured to be 9.2 ± 1.3. Other backgrounds include $Z \to \tau\tau$ production with τ decaying leptonically, and specifically for the muon channel, contamination from cosmic muons that are reconstructed as two muons and $b\bar{b}$ production where b quarks produce soft muons. The contribution from these backgrounds are estimated by studying leptonic Z decays and found to be 0.20 ± 0.03 for the electron and 0.9 ± 0.3 for the muon channel.

Overall, we estimate 4.7 ± 0.7 background events in electron and 10.1 ± 1.3 events in muon channels.

VI. RESULTS

The cross-section for $Z(\gamma)$ production times the branching ration for $Z(\gamma) \to \ell\ell\gamma$ is evaluated with the following formula

$$\sigma \cdot \mathrm{Br}(Z/\gamma^*(\gamma) \to \ell\ell\gamma) = \frac{\mathrm{N_{cand}} - \mathrm{N_{bkg}}}{\epsilon_{\ell\ell\gamma} \cdot \int \mathcal{L}dt}, \tag{1}$$

where N_{cand} and N_{bkg} are the number of candidate events and the estimated number of background events, $\epsilon_{\ell\ell\gamma}$ is the efficiency of the selection criteria, and $\int \mathcal{L}dt$ is the integrated luminosity of the data sample. We summarize the parameters that are used in calculation of the cross-section in Table I,

The cross-section for $Z(\gamma) \to ee\gamma$+X, where the di-lepton invariant mass is above 30 GeV/c^2, and the photon has $E_T > 8$ GeV and is separated from both leptons by $\Delta R_{\ell\gamma} > 0.7$ is measured to be $\sigma \cdot \mathrm{Br}(Z/\gamma^*(\gamma) \to ee\gamma) = 3.99 \pm 0.80(\mathrm{stat.}) \pm 0.25(\mathrm{syst.}) \pm 0.26$ (lumi.) pb. That for $Z(\gamma) \to \mu\mu\gamma$+X is measured to be $\sigma \cdot \mathrm{Br}(Z/\gamma^*(\gamma) \to \mu\mu\gamma) = 3.80 \pm 0.53(\mathrm{stat.}) \pm 0.14(\mathrm{syst.}) \pm 0.25$ (lumi.) pb. These results were combined using the Best Linear Unbiased Estimate (BLUE) [6] method, taking the uncertainty in the photon efficiency and that in the luminosity as completely correlated, and the other uncertainties as completely uncorrelated. The result is $\sigma(p\bar{p} \to Z(\gamma) + X \to \ell\ell\gamma + X) = 3.86 \pm 0.46(\mathrm{stat.} + \mathrm{syst.}) \pm 0.25(\mathrm{lumi.})$ pb. The cross-section calculated by the Baur Monte Carlo simulation using CTEQ5L PDF is 4.3 pb.

The di-lepton mass as a function of the di-lepton plus photon invariant mass is illustrated in Fig. 2. The photon E_T spectrum, as well as the separation from a photon candidate and the leptons are given in Figs. 3-6 for the electron and muon channels.

In Fig. 7 we plot the measured cross-section as a function of the threshold on the photon candidate's transverse energy. Results are stable for all values of the threshold E_T.

VII. SUMMARY

The cross-section times branching fraction for events with both a Z boson and a photon has been measured at center-of-mass energy $\sqrt{s} = 1.96$ TeV. Data comprising 177(144) pb^{-1} of $p\bar{p}$ collisions was obtained by the DØ Experiment in 2002 and 2003 in the electron (muon) decay mode. For a minimum di-lepton mass of 30 GeV/c^2, minimum photon transverse energy of 8 GeV and for a minimum lepton-photon separation $\Delta R_{\ell\gamma} > 0.7$, 33(68) events were observed. These events include both those with a photon radiated from the final state lepton and those originated in the collision. The combined result is $\sigma(p\bar{p} \to Z(\gamma) + X \to \ell\ell\gamma + X) = 3.90 \pm 0.51(\mathrm{stat.} + \mathrm{syst.}) \pm 0.25(\mathrm{lumi.})$ pb. It is consistent with the Standard Model prediction.

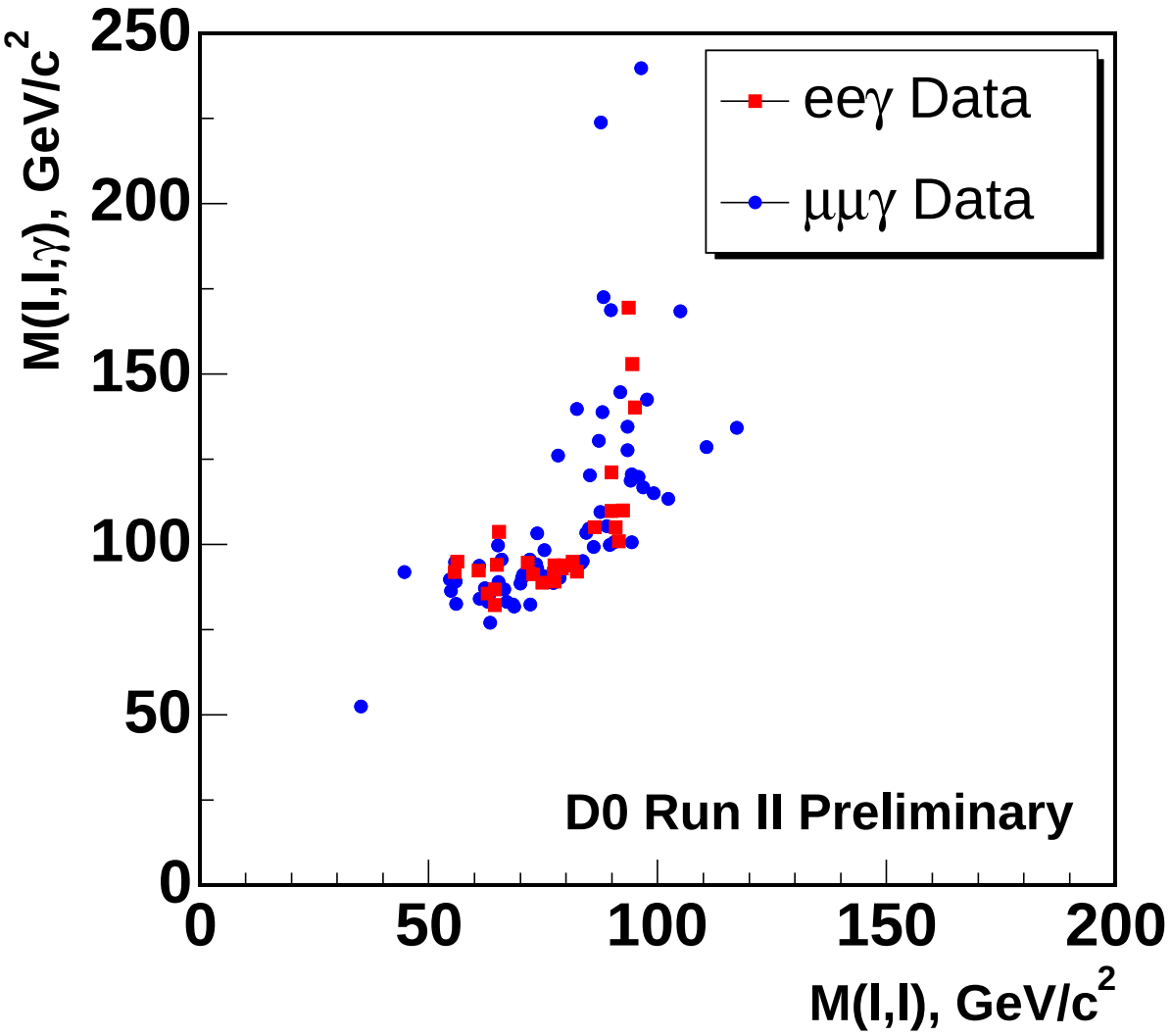

FIG. 2: Invariant mass of the di-lepton system vs. invariant mass of di-lepton and a photon candidates.

Acknowledgments

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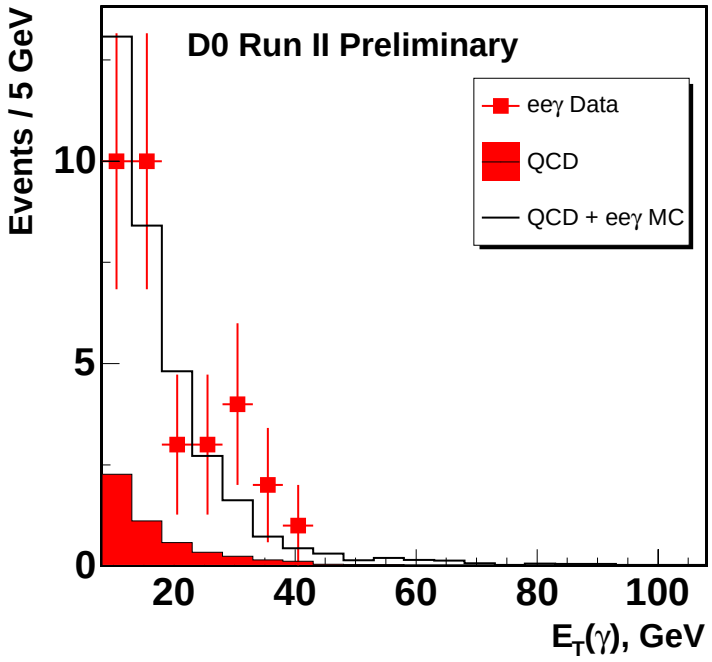

FIG. 3: Photon candidate E_T spectrum for $Z(\gamma) \to ee$ data (red squares), Monte Carlo (histogram), and QCD background (shaded histogram).

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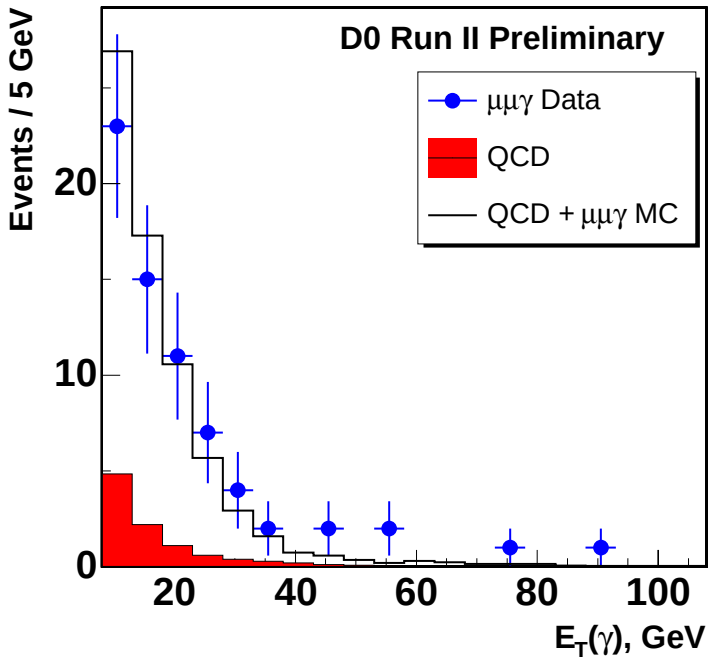

FIG. 4: Photon candidate E_T spectrum for $Z(\gamma) \to \mu\mu\gamma$ data (blue circles), Monte Carlo (histogram), and QCD background (shaded histogram).

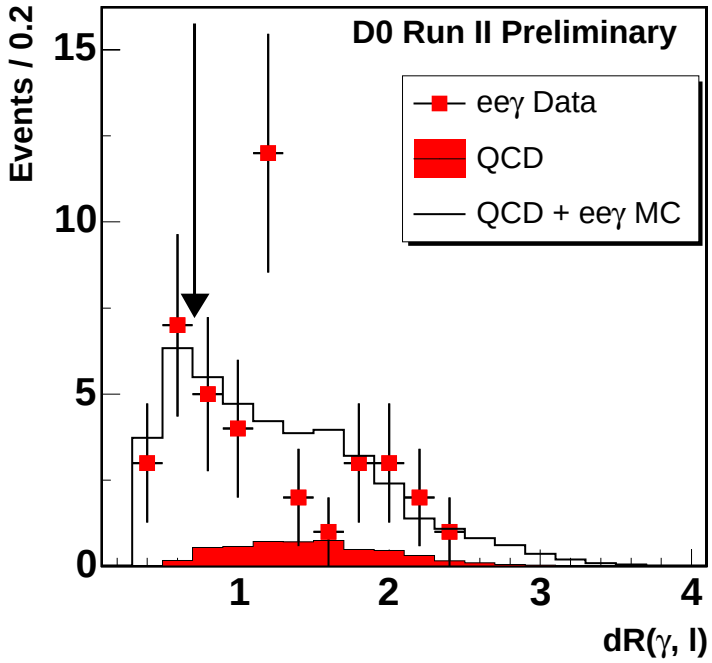

FIG. 5: The smallest separation in $\Delta R_{\ell\gamma}$ between the photon and leptons for $Z(\gamma) \to ee\gamma$ data (red squares), QCD background (shaded histogram), and Monte Carlo prediction with QCD background (solid histogram). We reject photon candidates with $\Delta R_{\ell\gamma}$ below 0.7 (to the left of the arrow).

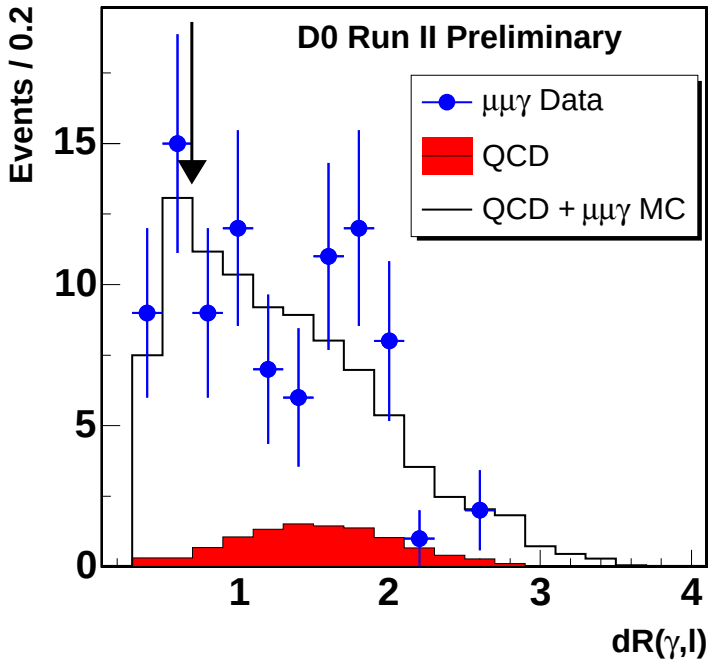

FIG. 6: The smallest separation in $\Delta R_{\ell\gamma}$ between the photon and leptons for $Z(\gamma) \to \mu\mu\gamma$ data (blue circles), QCD background (shaded histogram), and Monte Carlo prediction with QCD background (solid histogram). We reject photon candidates with $\Delta R_{\ell\gamma}$ below 0.7 (to the left of the arrow).

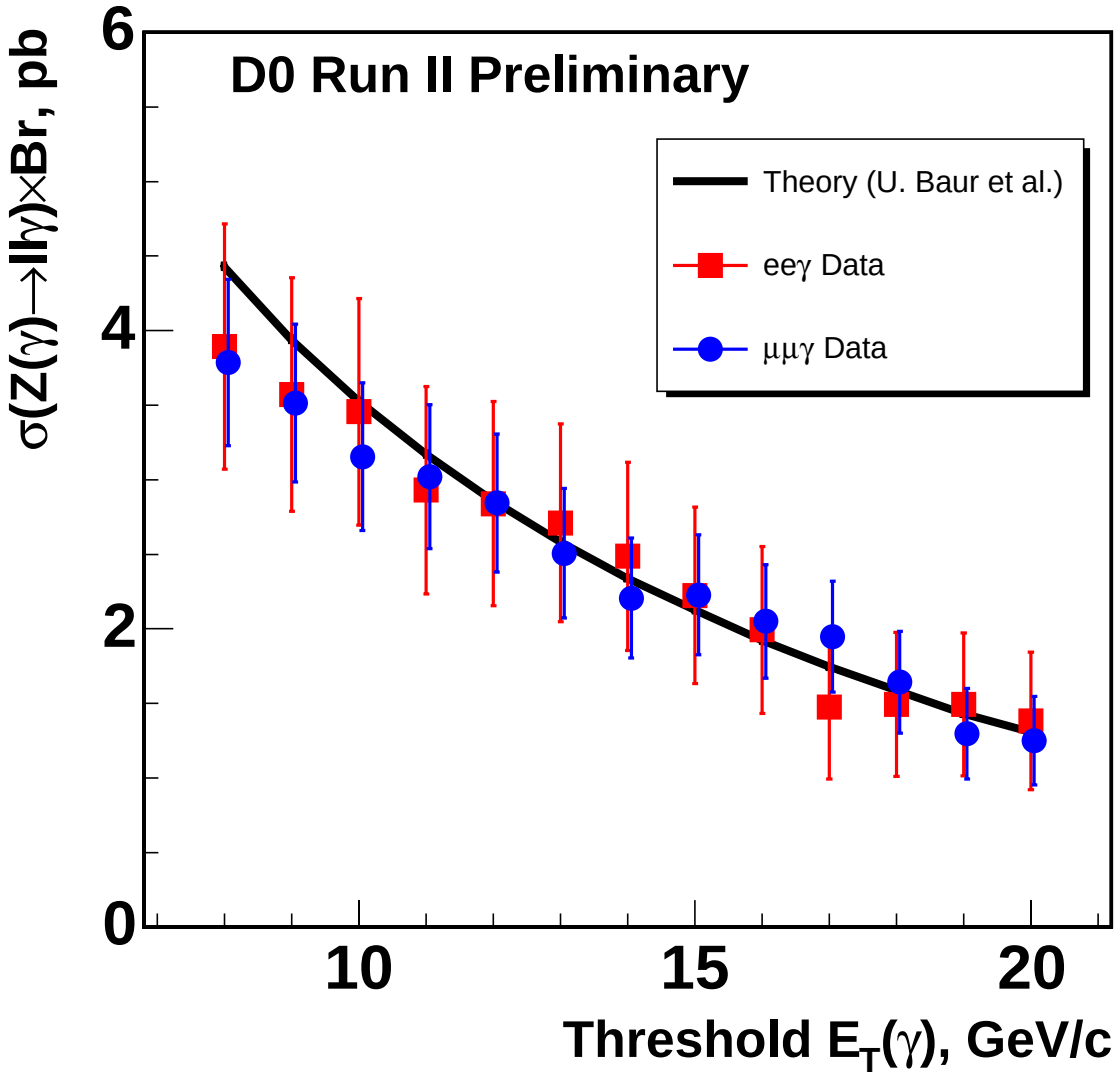

FIG. 7: The measured cross-section of $Z(\gamma) \rightarrow \ell\ell\gamma$ process as a function of the threshold on the photon E_T. Red circles correspond to cross-section measurements in electron channel, and blue squares are that in muon channel. The line represents the theoretical cross-section [2, 3] as a function of minimum photon E_T.