Measurement of final-state radiation in leptonic decays of Z boson

Tomasz Bednarek, University of Lodz, Poland

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Abstract

This report is on the measurement of final-state radiation in dielectron and dimuon decays of Z boson for a data sample gathered at $\sqrt{s} = 13$ TeV in years 2015-2016 from the ATLAS detector. The differential cross section for the radiative Z boson decay with respect to various kinematic and physical quantities such as photon pseudorapidity η_γ, photon transverse momentum $p_{T,\gamma}$, the nearer lepton-photon distance $\Delta R_{l\gamma}$ and the invariant mass of the dilepton + photon system $m_{ll\gamma}$ is measured and compared to the POWHEG predictions in fiducial region for dielectron and dimuon decay. The cross section ratio between the radiative decays $Z \to l^- l^+ \gamma$ and non-radiative decays $Z \to l^- l^+$ is also measured and compared for both channels of decay.

Contents

1 Introduction

The phenomenon of radiative Z boson decays were firstly noted in the very first Z boson publications of UA1 [1] and UA2 collaborations [2]. Recently there were published two papers concerning topic: one from the CMS Collaboration from 2015 on final-state radiation (FSR) in decays of Z bosons at 7 TeV [3], and the other from the ATLAS Collaboration from 2016 on the production of Z bosons with one or two isolated high-energy photons at 8 TeV [4]. In this study we analyse the data collected by the ATLAS detector at centre-of-mass energy $\sqrt{s} = 13$ TeV.

Non-radiative leptonic decays of Z boson are referred to as Drell-Yan production (DY). Quantum corrections to DY processes are well-described and their cross sections distributions are well-measured. However, in case of the FSR processes QCD (Quantum Chromodynamics) and QED (Quantum Electrodynamics) mixed corrections are challenging to compute photons, and often the event generators based on matrix element calculations matched to parton showers are used. Furthermore, photons emitted in the FSR processes can be very energetic (tens of GeV), and well-separated spatially from the leptons – hence the measurement of differential cross section as a function of photon kinematic quantities is a good test of the electroweak sector of the Standard Model – e.g. constraints on the triple and quartic boson couplings have been put by different experiments such as LEP, the Tevatron or the LHC [5].

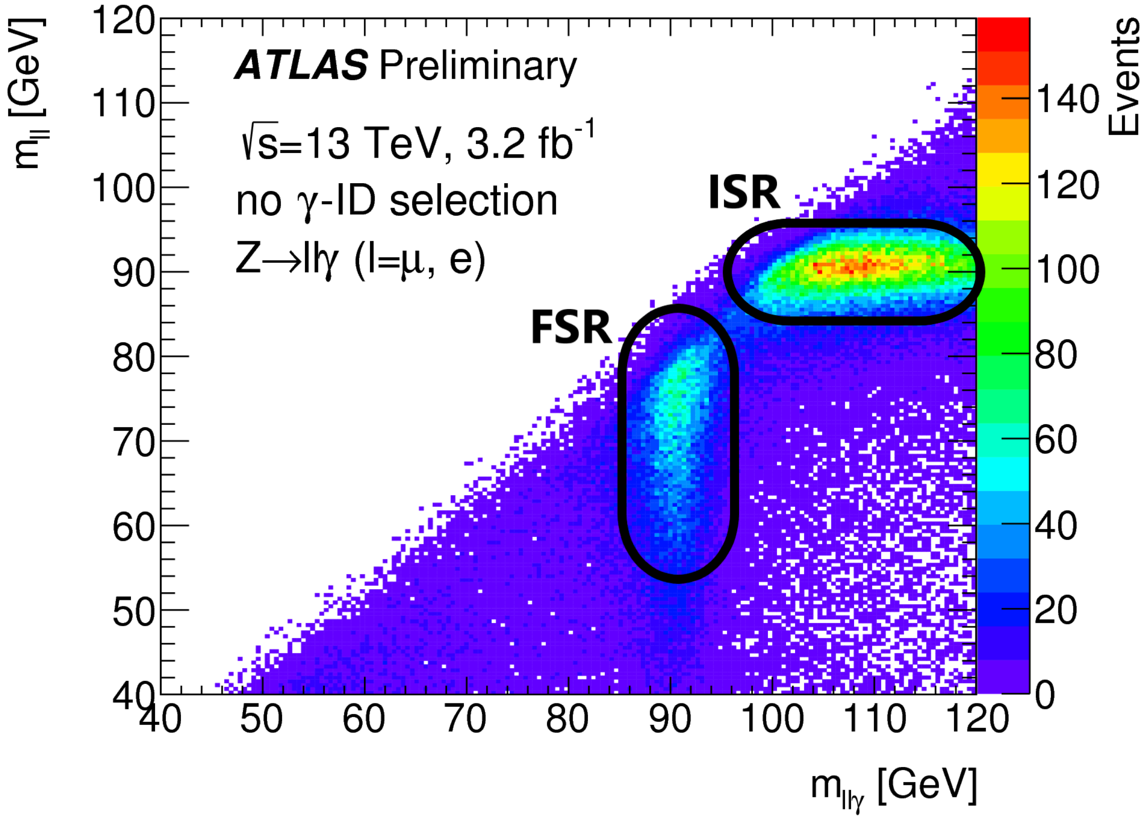
1.1 Objectives of the project

Final-state radiation from Z boson decays is a background to the processes with photons and leptons in the final state, therefore it is quite important to investigate this process as accurately as possible. Furthermore, the measurement of differential cross section as a function of kinematic quantities, such as photon pseudorapidity η_γ, photon transverse momentum $p_{T,\gamma}$, invariant mass of the system $m_{ll\gamma}$ and distance between the nearer lepton and the photon $\Delta R_{l\gamma}$ is important and can be compared later to the Monte Carlo predictions. Accounting for the resolution and reconstruction effects in the detector, and to simplify the comparison between predictions from various Monte Carlo generators and as well as different experiments, the unfolding procedure is applied to data to obtain fiducial (differential) cross sections. Given that, we will be able to compare various Monte Carlo predictions and find the most suitable generator properly describing the radiation processes.

2 Applied selection on Monte Carlo samples and data

2.1 Signal selection of radiative decays

Firstly, let us consider signal selection cuts for the radiative decays $Z \to l^- l^+ \gamma$. It is required for the more energetic lepton from the pair to have transverse momentum $p_{T,l_1} > 30$ GeV, and correspondingly for the second one $p_{T,l_2} > 25$GeV. Moreover, the cut on the transverse momentum of the photon is set to be $p_{T,\gamma} > 15$ GeV. According to the below graph of two-dimensional distribution of reconstructed radiative decay events with respect to the invariant mass of the lepton pair (y axis) and the invariant mass of the dilepton + photon system (x axis) [6]



Two-dimensional distribution of $m_{ll\gamma}$ and m_{ll} for all reconstructed $Z \to l^- l^+ \gamma$ events [6]

the selection based on aforementioned invariant masses may be applied to differentiate between initial-state radiation processes and the final-state radiation ones. As it follows from the distribution, the FSR events have a peak for the invariant mass of photon-dilepton system $m_{ll\gamma}$ being close to the Z boson resonance (ca. 90 GeV), and the ISR events – on the other hand – they peak around the invariant mass of the lepton pair m_{ll} being close to the Z resonance. This means that it is justified to use the cut on the invariant mass of the dilepton + photon system: 66 GeV $< m_{ll\gamma} <$ 103 GeV with one on the invariant mass of the lepton pair: one on the invariant mass of the lepton pair: $m_{ll} >$ 40 GeV in order to significantly reduce the number of ISR events and non-Z processes. We also apply standard ATLAS cuts on pseudorapidities of resultant particles – for electrons and photons we need to consider the crack removal for the $1.37 < |\eta| < 1.52$ due to the construction of the ATLAS electromagnetic calorimeter. On the other hand for muons we do not have any kinds of crack regions. Photons acceptance on pseudorapidity is $|\eta| < 2.37$, for electrons $|\eta| < 2.47$, and for muons $|\eta| < 2.50$. We also want to search for photons being emitted not too close from leptons, therefore we want a physical distance in the η-ϕ space between the nearer lepton and the photon, defined as $\Delta R_{l\gamma} = \sqrt{(\phi_l - \phi_\gamma)^2 + (\eta_l - \eta_\gamma)^2}$, to be $\Delta R_{l\gamma} > 0.4$. There are also standard quality and isolation criteria applied to photons and leptons as well.

2.2 Fiducial selection of radiative decays

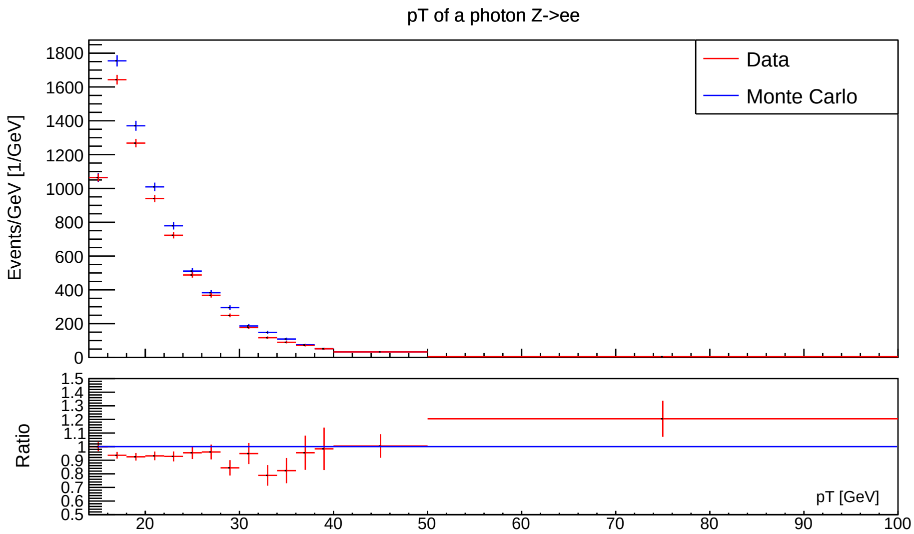
Selection on the transverse momenta of resultant particles p_{T,l_1}, p_{T,l_2} and $p_{T,\gamma}$, invariant mass of the lepton pair one on the invariant mass of the lepton pair m_{ll} and dilepton + photon system $m_{ll\gamma}$, and the spatial separation between the photon and the nearer lepton $\Delta R_{l\gamma}$ is the same as in case of signal selection. The selection on the invariant mass of the lepton pair Cuts on the pseudorapidities, however, do not include the crack removal and they are uniform for both types of leptons – that is $|\eta_l| < 2.47$. For the photon pseudorapidity we require $|\eta_\gamma| < 2.37$ without crack removal as well. There is however additional isolation criterium on the photon: ETcone20 $< 0.05 \cdot p_{T,\gamma}$. ETcone20 is a scalar sum of transverse momenta for all particles with lifetime longer than 10 ps (except neutrinos and muons) within a cone of a radius $\Delta R = 0.2$ around the photon.

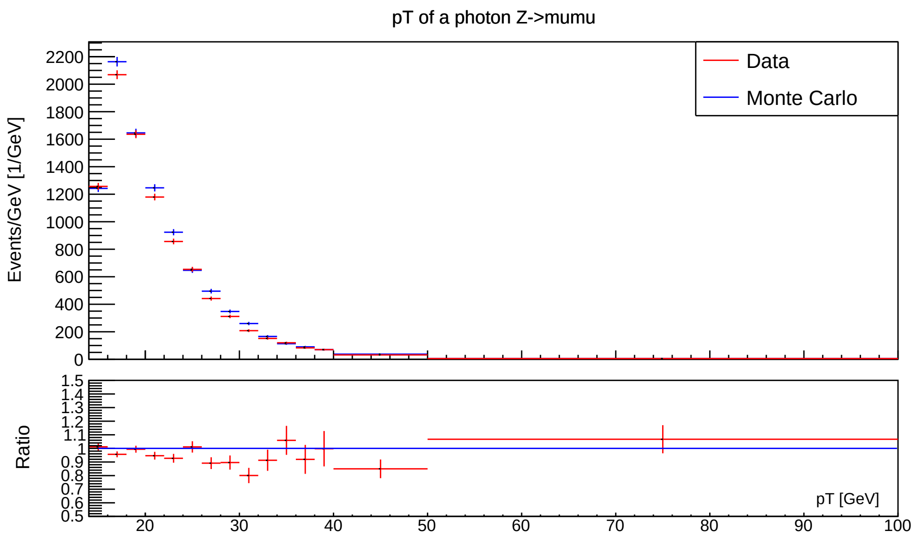
2.3 Fiducial and detector selection of non-radiative decays

As one of the objectives is to measure the ratio of final-state radiation cross section to the Z boson decay cross section, we also need to apply corresponding fiducial and detectors cuts, so that the distributions are comparable. In both volumes we apply the same selection on transverse momenta of the lepton pair and on the invariant mass of the dilepton system, as in the signal selection subsection. The difference between selection in aforementioned volumes appears only in the pseudorapidity cut, as for the detector one we have again $|\eta_e| < 2.47$ with crack removal for electrons, and $|\eta_\mu| < 2.5$ for muons. In case of the fiducial volume, we have instead the uniform pseudorapidity acceptance $|\eta| < 2.47$ for both flavours of leptons.

3 Comparison between Monte Carlo and data

Monte Carlo samples used in this study consist of inclusive Z processes generated with POWHEG. Researched data sample is 13 TeV data sample collected by the ATLAS collaboration in 2015-2016 years, and its luminosity is $36.2\,\mathrm{fb}^{-1}$. In order to have the first estimation of the agreement between data sample and Monte Carlo predictions in the recoil volume, we plotted below the distributions of transverse momentum of the photon in radiative decays for both channels $Z \to e^- e^+ \gamma$ and $Z \to \mu^- \mu^+ \gamma$.





Comparison of distributions of photon transverse momentum $p_{T,\gamma}$ for data (red) and Monte Carlo predictions (blue) for both decay channels

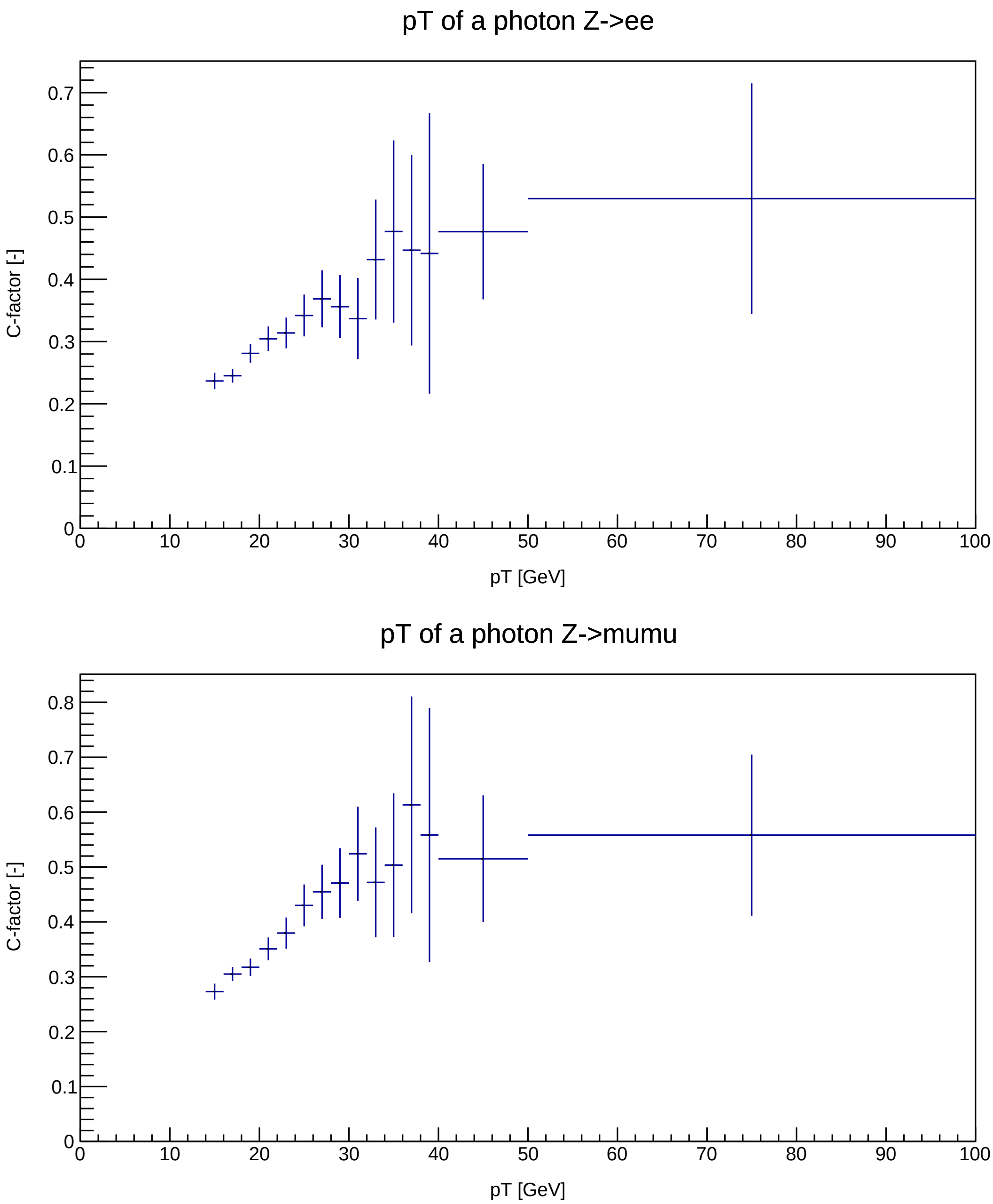
It is worth noticing that here Monte Carlo points are higher than data (i.e. the ratio between data and Monte Carlo points is below 1), and usually the inverse situation occurs – as some of background processes are neglected in the Monte Carlo simulation, then often one gets underestimation of number of occurring events, which is not being observed here. The main source of background is a number of wrongly reconstructed $Z+$ jets events as radiative decays, yet they give negligible contribution lower than 5%. Even though we neglected the background, we still observe an agreement within uncertainties between the prediction and the obtained data, and it means that after unfolding procedure, at least the same level of agreement can be expected.

4 Unfolding procedure

In order to easily compare data between different experiments and theoretical/Monte Carlo predictions, there occurs a necessity to account for the detector unwanted effects, such as reconstruction efficiency or errors related to triggers. Therefore a fiducial phase space is usually defined as a phase space well defined theoretically and as close to the detector phase space as possible. Due to those reasons, in this study the bin-by-bin unfolding correction is being applied to data – 10-million-entry Monte Carlo samples for both decay channels were generated and processed through both detector cuts and fiducial cuts. Later, those two resultant samples are compared to each other, and corresponding distribution from both samples are divided bin-by-bin, giving us the C-factor distributions. C-factor stands for the correction factor being the ratio of the number of signal events to the number of fiducial events, and it appears as we have the (differential) cross section dependence on the number of signal events N_i^{sig} in i-th bin, shown via below expressions

$$\sigma_i = \frac{N_i^{\mathrm{sig}}}{C_i \int L\,dt} \qquad \text{and} \qquad \frac{d\sigma_i}{dx} = \frac{N_i^{\mathrm{sig}}}{C_i\,\Delta x_i \int L\,dt} \tag{1}$$

where $C_i = N_i^{\mathrm{sig}}/N_i^{\mathrm{fid}}$ is the C-factor for the i-th bin, $\int Ldt$ is the total luminosity and x represents here a quantity with respect to which the differential cross section is calculated/measured. Therefore, if we know the C-factor bin-by-bin for various distributions, then it is easy to obtain fiducial distributions from the measured detector ones simply by dividing them by C-factor. One of the C-factor distributions for both decay channels is depicted below



C-factor dependence on the photon transverse momentum $p_{T,\gamma}$

for both channels of Z boson decay

There is a noticeable dependence on the obtained C-factor with respect to the transverse momentum of the photon $p_{T,\gamma}$, as objects with higher p_T tend to be better reconstructed (the photon identification efficiency increases with p_T), and as well isolation efficiency increases with the transverse momentum.

However, in case of the cross section ratio $\sigma_{Z\gamma}/\sigma_Z$, one needs to unfold both numerator and denominator (as they correspond to different processes), hence we will have four independent C-factors (accounting for both decay channels), which are shown below

Decay mode	Non-radiative decay	Radiative decay	Ratio
$Z \to e^- e^+ (\gamma)$	0.62140 ± 0.00059	0.290 ± 0.012	2.141 ± 0.047
$Z \to \mu^- \mu^+ (\gamma)$	0.72883 ± 0.00065	0.346 ± 0.013	2.103 ± 0.043

C-factors for non-radiative and radiative decays cross sections and their ratio

It is worth noticing that C-factors differ depending on the channel which is given by the fact that electron and muon detection efficiencies are different (i.e. different detectors and e.g. pseudorapidity acceptance). Moreover, as we have smaller statistics on the radiative decays compared to the non-radiative, the statistical uncertainty is greater for the former – therefore being the main contributor to the uncertainty for the ratios. However, for the cross-section-ratio C-factor we obtain the same result within one-sigma uncertainty, which would be the sign that many of detectors effects cancel out while considering ratios of corresponding cross sections.

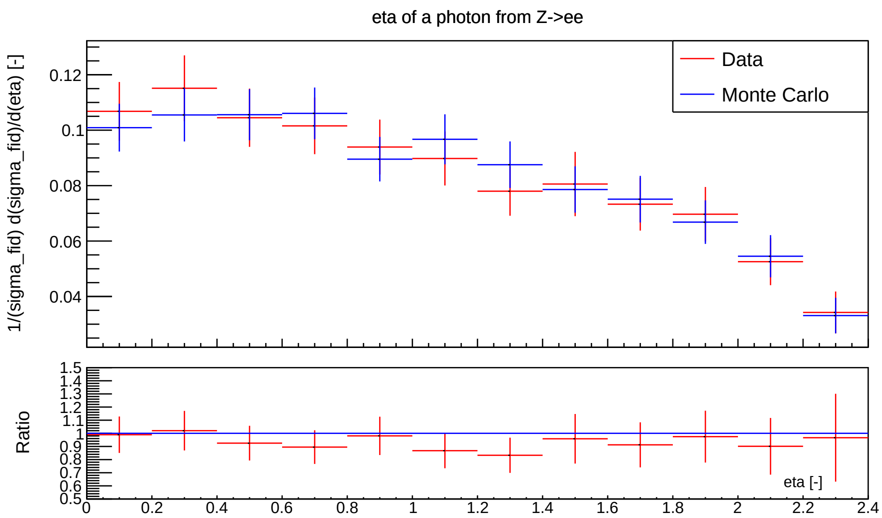
5 Obtained results

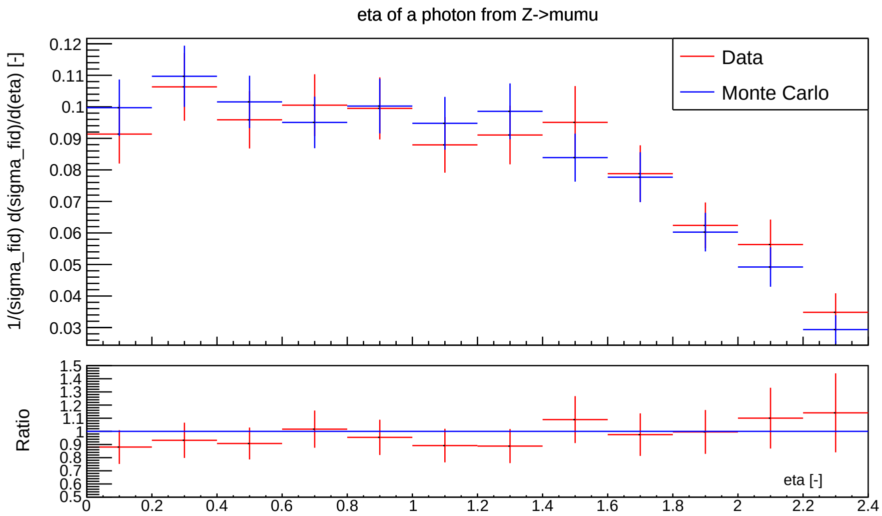
After applying bin-by-bin unfolding procedure, the cross section ratio between radiative and non-radiative decays of Z boson has been obtained for both channels

Decay mode	Unfolded data	Monte Carlo prediction
$Z \to e^- e^+$	$(2.010 \pm 0.049) \cdot 10^{-3}$	$(2.082 \pm 0.053) \cdot 10^{-3}$
$Z \to \mu^- \mu^+$	$(2.115 \pm 0.046) \cdot 10^{-3}$	$(2.207 \pm 0.041) \cdot 10^{-3}$

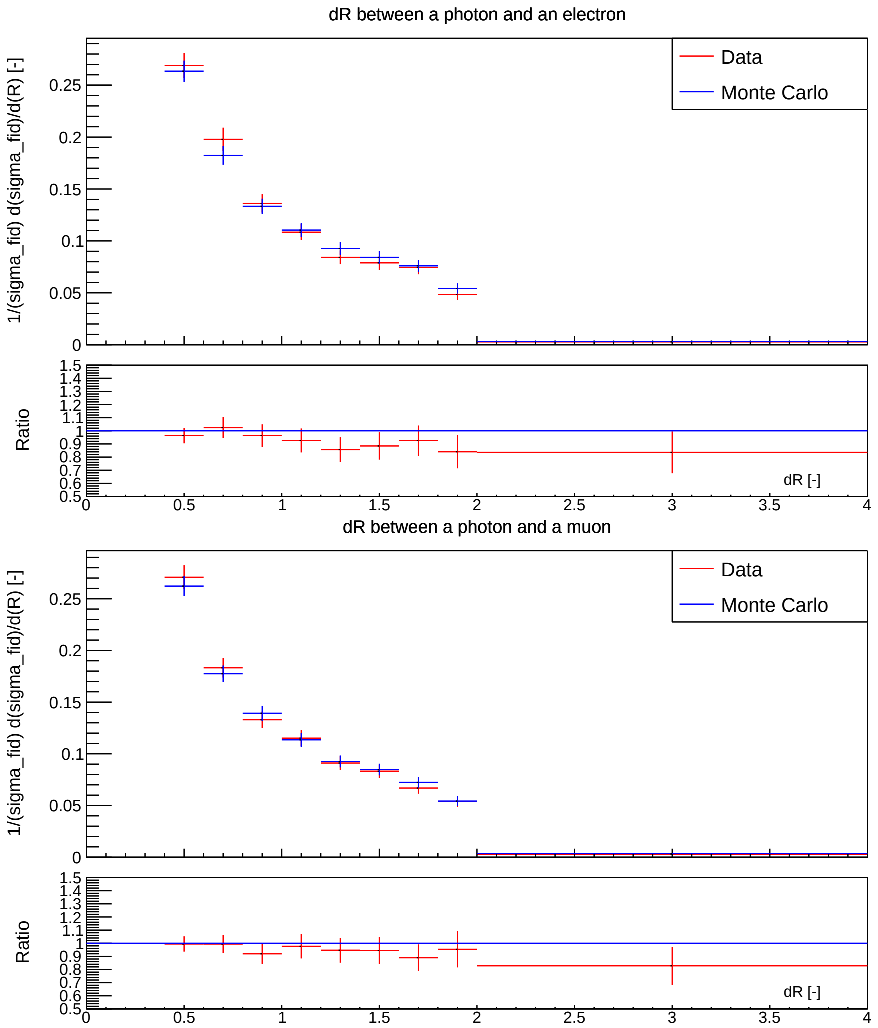
Comparison of cross section ratio $\sigma_{Z\gamma}/\sigma_Z$ for unfolded data and Monte Carlo prediction

It is easy to notice the agreement between values within two-sigma level, which is reasonable, especially as we neglect the $Z+$ jets background. We also can notice the two-sigma agreement between the ratios for both channels, as they should be equal to each other due to the lepton universality. Furthermore, the differential cross sections in fiducial region were measured with respect to various kinematic and physical quantities, such as photon pseudorapidity η_γ, photon transverse momentum $p_{T,\gamma}$, invariant mass of dilepton + photon system $m_{ll\gamma}$, and the distance between the nearer lepton and the photon $\Delta R_{l\gamma}$. They were compared to the Monte Carlo predictions in the fiducial volume as well. The resultant plots (normalised to unit area) are depicted below

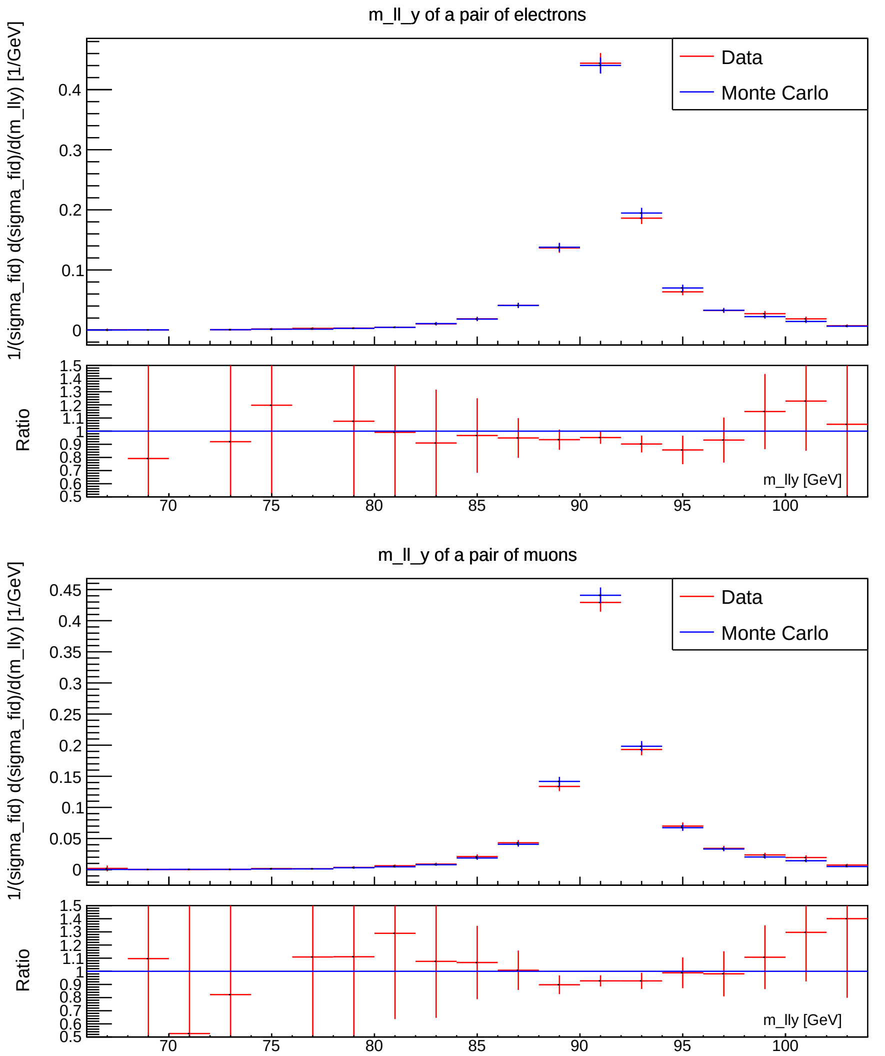




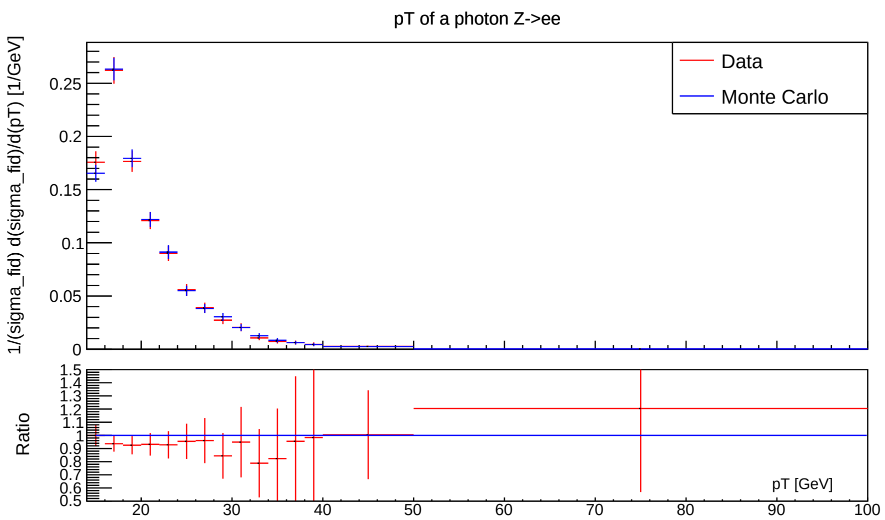
Distributions of η_γ for the $Z \to l^- l^+ \gamma$ events in the fiducial region

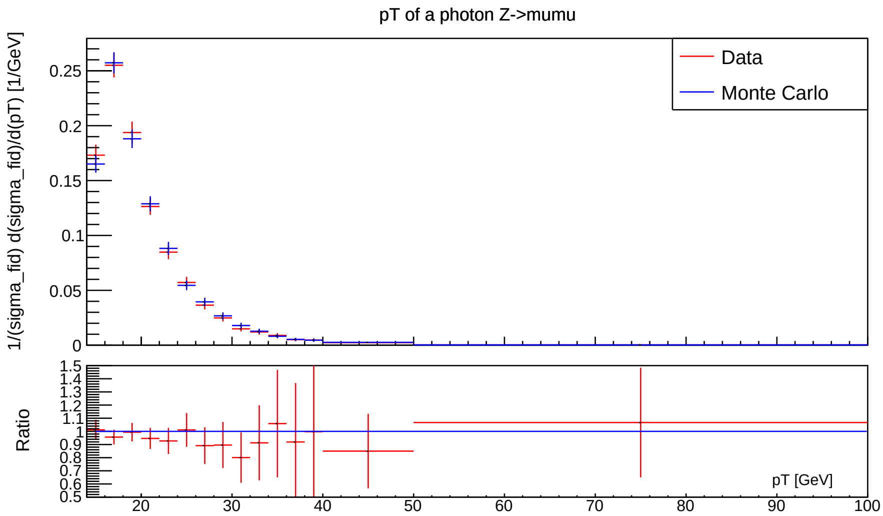


Distributions of $\Delta R_{l\gamma}$ for the $Z \to l^- l^+ \gamma$ events in the fiducial region



Distributions of $m_{ll\gamma}$ for the $Z \to l^-l^+\gamma$ events in the fiducial region





Distributions of $p_{T,\gamma}$ for the $Z \to l^- l^+ \gamma$ events in the fiducial region

As far as one can gather, results after unfolding in the fiducial region show that we have an agreement within uncertainites between Monte Carlo predictions and data sample gathered at ATLAS within 5%. Uncertainties considered here in this study are only statistical, therefore e.g. for the highest p_T bins the statistical error is quite big due to the smaller statistics within the bin. The closest agreement between data and Monte Carlo predictions is obtained for the differential cross section with respect to the distance between the nearer lepton and the photon $\frac{d\sigma_{\text{fid}}}{d(\Delta R_{l\gamma})}$, and the highest discrepancy occurs for the differential cross section with respect to the invariant mass of the system $\frac{d\sigma_{\text{fid}}}{dm_{ll\gamma}}$.

6 Conclusions and outlook

Differential cross section with respect to photon pseudorapidity η_γ, photon transverse momentum $p_{T,\gamma}$, the nearer lepton-photon distance $\Delta R_{l\gamma}$ and the invariant mass of the dilepton + photon system $m_{ll\gamma}$ was measured and compared to the POWHEG predictions in the fiducial phase space. Furthermore, the cross section ratio between the radiative and non-radiative decays was also measured and compared with the Monte Carlo prediction, and between both channels of decay (due to the lepton universality). It has been found that the data and Monte Carlo agree within 5% uncertainty which is reasonable given the fact that the main source of background (i.e. wrongly reconstructed Z + jets events as the radiative ones) was neglected due to its non-significant contribution (less than 5%). Therefore we may conclude that POWHEG is quite accurate for modelling of the FSR processes, and it is planned to check other Monte Carlo generators in terms of accuracy and agreement with data e.g. for generated samples from SHERPA.

References

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