Measuring cross sections of Z boson decays with the ATLAS detector at the LHC

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The cross section of Z boson decays were measured using ATLAS OpenData from the LHC. Real data was compared with computer-simulated Monte Carlo data to make suitable selection cuts and eliminate unwanted background events. The data used corresponds to proton-proton collisions at a centre of mass energy $\sqrt{s} = 13$ TeV and an integrated luminosity of approximately 10 fb^{-1}. The results obtained for the cross-sections were $\sigma(Z \rightarrow \mu^+\mu^-) = 1.980 \pm 0.002(\text{stat}) \pm 0.001(\text{syst}) \pm 0.034(\text{lumi})$ nb and $\sigma(Z \rightarrow e^+e^-) = 2.025 \pm 0.002(\text{stat}) \pm 0.003(\text{syst}) \pm 0.034(\text{lumi})$ nb (within an invariant mass window $60 < m_{ll} < 120$ GeV), where the decay chain is given in brackets.

I. INTRODUCTION

ATLAS is a detector at the Large Hadron Collider (LHC) at CERN which measures the properties of the products of proton-proton (pp) collisions at high energies. The LHC is a *colliding-beam* particle accelerator which has an advantage over fixed-target accelerators in that it works at higher centre-of-mass energies. Centre-of-mass energy is important as it is a measure of the energy available to create new particles [1].

The weak interaction is associated with elementary spin-1 bosons which act as force carriers between quarks and/or leptons. These are relatively massive particles with a very short range and are known as intermediate vector bosons. The neutral vector boson Z^0 mediates processes called *neutral current* reactions [1, 2]. Measurements of the cross sections of Z boson decays constitute an important test of the Standard Model [3].

This report describes measurements of cross sections for leptonic decay channels of the Z boson, $Z \rightarrow l^+l^-$ ($l^\pm = e^\pm, \mu^\pm$). The cross section of a process represents the probability of that process taking place. All measurements are performed with pp collision data from ATLAS OpenData corresponding to an integrated luminosity of 10.064 fb^{-1}, collected at a centre-of-mass energy $\sqrt{s} = 13$ TeV. Integrated luminosity is proportional to the number of pp collisions in the data.

A. The ATLAS detector

The coordinate system and nomenclature used to describe the ATLAS detector and proton-proton collisions are summarised. ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the centre of the detector, while the anti-clockwise beam direction defines the z-axis. The x-axis is from the interaction point to the centre of the LHC ring, and the y-axis points upwards. Cylindrical coordinates are used in the transverse plane, with ϕ being the azimuthal angle around the beam axis. Pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$, where θ is the angle from the beam axis. The transverse momentum (p_T) is defined in the $x-y$ plane, as the detector is unable to measure the parallel component of momentum of the product particles [4, 5].

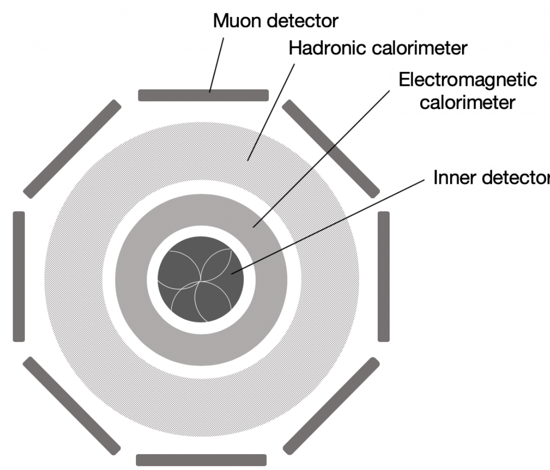

FIG. 1: A simplified schematic of a general purpose detector for proton-proton collisions such as ATLAS, viewed in the plane transverse to the beam direction.

The ATLAS detector consists of four primary regions as shown in Fig.1. The inner detector provides precision tracking of charged particles and is composed of silicon trackers immersed in a magnetic field; the momentum of the charged particles is measured from their curvature. Calorimeters are devices used to measure the total energy of particles or jets of particles by total absorption [6]. The electromagnetic calorimeter measures the total energy of charged particles; the hadronic calorimeter measures the total energy of neutral hadronic particles.

The outermost layer of the detector houses the muon spectrometer, which measures the momentum of muons based on magnetic deflection by large superconducting toroid magnets. A trigger system is used to reduce the total detector information into a manageable selection of events that are most likely to be of interest (i.e. high energy events) [3, 4, 7].

B. Z boson decays

Z bosons decay into a lepton-antilepton pair approximately 10% of the time; the leptonic decay channels each occur with near equal probability [8]. Using relativistic kinematics, the invariant mass of the Z boson parent particle can be found by applying conservation of four-momentum to the lepton-antilepton product pair. The process occurs at sufficiently high energy that the rest mass term can be neglected, and by making coordinate transformations to the measurable kinematic variables of the leptons, the invariant mass can be expressed as

$$m_{ll} = \sqrt{2p_{T_1}p_{T_2}(\cosh(\eta_1 - \eta_2) - \cos(\phi_1 - \phi_2))}. \quad (1)$$

II. EXPERIMENTAL METHOD

A data set from the 13 TeV ATLAS run comprised of events containing two or more leptons was available, along with a number of simulated data sets, commonly known as Monte Carlo (MC) data, produced from theoretical models for specific processes. These are important for comparing theoretical predictions with real data, and facilitate the design of 'selection cuts' that can be applied to select a sample of events in the real data that correspond to a specific process ('signal' events). When choosing selection cuts, a compromise must be made between achieving as high a selection efficiency for the signal as possible, and rejecting as much 'background' as possible resulting from other processes.

The cross sections for a targeted process can be expressed as

$$\sigma(pp \to Z \to ll) = \frac{N^{selected} - N^{background}}{\epsilon \int Ldt}, \quad (2)$$

where $N^{selected}$ is the total number of events in the ATLAS data that pass the selection cuts, $N^{background}$ is an estimate of the number of background events in the selected data, ϵ is the efficiency, and $\int Ldt$ is the integrated luminosity. Thus, $N^{selected} - N^{background}$ is the estimate of the number of signal events in the ATLAS data for a targeted process, in this case, a Z boson decaying into oppositely charged leptons. Efficiency ϵ is calculated using the Monte Carlo simulation for the relevant decay, by running a preliminary python script *TotExpected.py*; and is equal to the number of signal MC events that pass the selection cuts, divided by the total number of generated signal events in the relevant MC sample.

A script was created for producing histograms from the data using ROOT - a framework designed at CERN to analyse large data sets [9]. A histogram computed using equation 1 is shown in Fig.2.

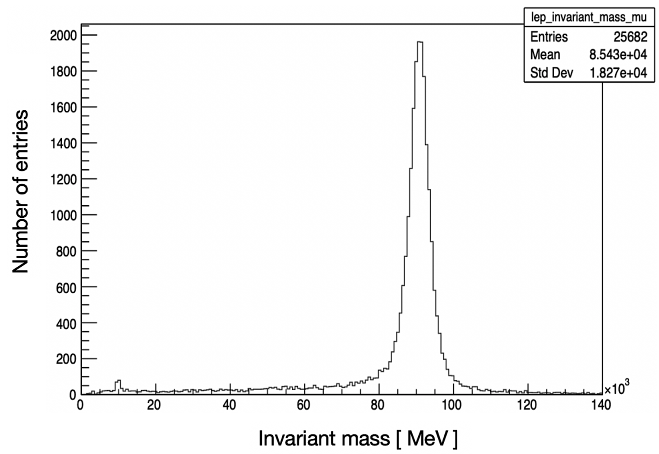

FIG. 2: Invariant mass distribution for a portion of the real ATLAS data with no cuts applied. The peak corresponds to the Z boson decaying into two muons with a system invariant mass of about 90 GeV.

For the backgrounds, the following processes were considered: $Z \to \tau\tau$, W boson decays, $t\bar{t}$ decays, Higgs decays, and ZZ^* pair decays. In the case of Z bosons, contributions from jets in the background are negligible [10]. The MC simulations are summed together to estimate the total number of background events, which are used to calculate the cross sections.

A. Making selection cuts

Initial selection criteria imposed on the data restricted signal events to those with *oppositely charged* leptons of the *same type*. For events with more than two leptons, the leptons with the highest p_T are selected. Histograms produced from MC data for $Z \to \mu^+\mu^-$ and $Z \to e^+e^-$ processes each have a peak approximating that shown in Fig.2 at 90 GeV. The main difference between these plots are that the simulated data has a lower cut-off at $m_{ll} =$ 60 GeV, implying that data below this value can be approximated as background. Consequently, an invariant mass selection cut of 60-120 GeV was chosen, approximately symmetric about the peak.

Leptons produced in Z boson decays tend to be 'isolated' from other product particles in pp collisions; an isolated lepton is one that does not have many other particles nearby. Utilising this fact for the selection cuts, the two isolation variables are defined as follows. ptcone30 is the sum over all p_T within a cone of $\Delta R = 0.3$ around the lepton (excluding the lepton p_T); ΔR is the half-width of the cone defined as $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$, where

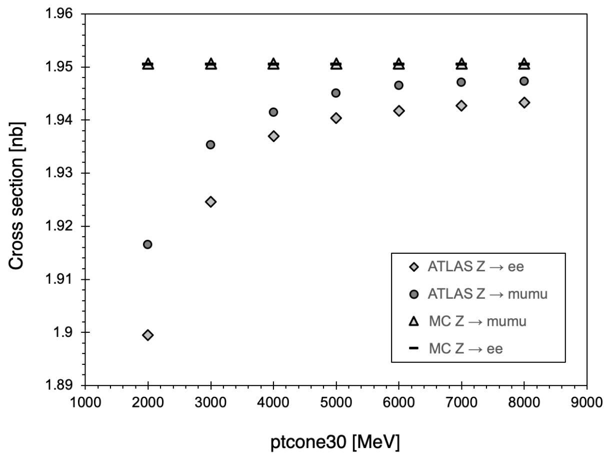

FIG. 3: Variation of cross section with ptcone30 selection cut. Note that the cross section values are constant in the MC data.

$\Delta\phi$ and $\Delta\eta$ are, respectively, the differences in azimuthal angle and pseudorapidity between the lepton and any additional particles. Similarly, etcone20 is the sum of the energy deposits in the calorimeters due to additional particles in a cone of $\Delta R = 0.2$ around the lepton.

The cross section was plotted as a function of each variable. The chosen ptcone30 selection cut is 7000 MeV, as this is where the cross section stabilises (Fig.3), so includes most of the signal events while discarding background. A similar plot and argument was made for the etcone20 cut, with a final value of ±6000 MeV.

III. RESULTS AND DISCUSSION

The measured cross sections for the two decay modes are shown in Table I. These are derived by applying equation 2 to the data that passed the selection cuts described in section II, and the background estimate.

Decay channel	Cross section (nb)
$Z \to \mu^+\mu^-$	$1.980 \pm 0.002(\text{stat}) \pm 0.001(\text{syst}) \pm 0.034(\text{lumi})$
$Z \to e^+e^-$	$2.025 \pm 0.002(\text{stat}) \pm 0.003(\text{syst}) \pm 0.034(\text{lumi})$

TABLE I: Calculated cross sections for the two Z boson decay modes studied with statistical (stat), systematic (syst), and luminosity (lumi) errors given in nanobarns.

Uncertainty on the cross section is separated into three types. The statistical error was taken as the Poisson uncertainty associated with the total number of events; for a histogram of count N the statistical error is equal to $\sqrt{N}$. As the data sets are very large the statistical error was small, about 0.1%. The standard deviation of the cross section as a function of the ptcone30, etcone20 and invariant mass cuts provided a systematic error of approximately 0.1%. All cuts provided a similar contribution to the systematic error, with no particular cut dominating. Note that the cross section should be independent of the isolation variable cuts. The accuracy of the cross section measurements are dominated most prominently by the luminosity uncertainty quoted at ±1.7% [11].

IV. CONCLUSION

The measurements of the cross sections of Z boson decays using ATLAS OpenData confirm certain predictions of the Standard Model, specifically that the decay probabilities are approximately equal between the leptonic decay channels. Improvements could me made to ensure that the two cross section values are compatible, as the systematic error here may be an underestimate. In addition, other sources of background (e.g. high energy photon decays) could have been investigated, and the statistical uncertainty improved by using a larger data sample.

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