Analysing Events with Z Bosons with the ATLAS Experiment

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Calculations of production cross section for Z boson decay in high energy proton-proton collisions have been calculated from the ATLAS open data at the Large Hadron Collider(LHC) at the centre of mass energy $\sqrt{s} = 13TeV$. The Z boson decay path to two opposite charge, same flavour leptons yielded results $\sigma_Z^{e^+e^-} 1.930 \pm 0.001(stat.) \pm 0.058(syst.) \pm 0.033(lumi.)nb$ and $\sigma_Z^{\mu^+\mu^-} 1.933 \pm 0.001(stat.) \pm 0.066(syst.) \pm 0.033(lumi.)nb$ for electrons and muons respectively. The systematic uncertainty arises from unaccounted backgrounds and disagreements between the Monte Carlo simulation and the real ATLAS data. The selection criteria for events were used to maximise the elimination of the background and reduce systematic uncertainty. Calculations of the transverse momentum distribution of the Z boson and the event selection cuts applied in this experiment are also presented. The cross-section calculations provide evidence for Lepton universality.

I. INTRODUCTION

This paper discusses the production cross-sections of the Z boson's leptonic decay paths and the method used to calculate these values. The data is obtained from the ATLAS Open Data released by the ATLAS Collaboration[1]. The data is from proton-proton collisions detected by the ATLAS detector at LHC at centre-off-mass energy $\sqrt{s} = 13TeV$ during the year 2016 and corresponds to an integrated luminosity of $10fb^{-1}$. Included alongside the data set are computer-simulated events as described by the standard model referred to as the Monte Carlo data set.

These cross-section results and the method involved allow the mass of the Z boson to be calculated and creates the ability to check the legitimizes of the standard model, such as Lepton universality. The cross-section is the probability of the process happening; therefore, the expected cross-sections for both leptons should be equal.

Histograms were plotted by a python script and then analysed. This script allowed us to plot a variable of these events, such as transverse momentum, against number of entries per bin and choose selection criteria to select events that only come from Z boson decay and simultaneously remove as much background as possible.

II. THEORY

The Z boson is a neutral elementary particle that carries the weak force[2]. It has a mass of $92.1GeV$ [3]. In proton-proton collisions Z bosons are created by quark anti-quark annihilation of the same flavour. The quark anti-quark is produced by a proton emitting a gluon which decays into the quark anti-quark pair[4]. Z bosons can also be produced in a stream of particles by a particle carrying colour change that decays, known as a jet.

A. Invariant Mass

The invariant mass of the Z boson can be calculated from the two daughter particles.

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

where p_T is transverse momentum, the momentum perpendicular to beam direction. η is pseudorapidity, the angle of particle relative to the beam axis. In this experiment pseudorapidity is less than 2.5, as greater than this the particles escape the detector. ϕ is the azimuthal angle between transverse momentum and the x-axis.

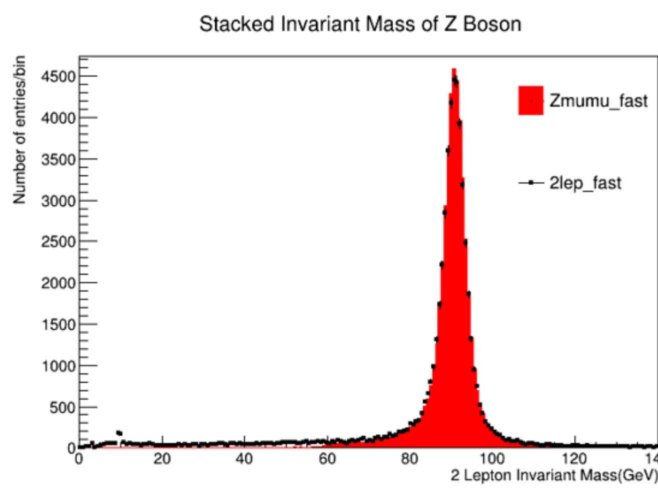

FIG. 1. Stacked invariant mass plot with real data(2lep) and Monte Carlo(Zmumu). This is after all cuts are applied. The upsilon meson peak is visible at 9GeV. The invaraint mass was calculated using equation (1).

The mass of the Z boson can be taken from this figure at around $90GeV$ as expected. In the real data there is a small secondary peak around $9GeV$ which can be identified as an upsilon meson.

B. Cross Section

The cross section is the probability of the process happening, by calculating this for two families of leptons we can look for standard model agreements or violations.

$$\sigma = \frac{N^{selected} - N^{background}}{\varepsilon \int Ldt} \tag{2}$$

$N^{selected}$ is the total number of events after selection cuts and $N^{background}$ is the number estimate for the background events. ε is the efficiency of selecting signal events, where signal means the Z decay we are measuring the cross section for. $\int Ldt$ is the integrated luminosity, the measure of proton-proton collisions in ATLAS to which the data set corresponds.

C. Event Selection and Background

Investigating figure 1, a upsilon meson can be found at 9GeV. An upsilon meson consists of a bottom anti-bottom quark. The bottom quark decays by the W^- boson to a lepton and neutrino. This dominates the low transverse momentum as gluons to bottom quark interaction favours low energy/mass due to asymptomatic freedom, which is the relation of stronger binding and therefore stronger interaction to lower energy, as seen in figure 3. In addition to bottom anti-bottom, top anti-top and tau leptonic decays, contribute to the background events in this experiment. Furthermore, Monte Carlo invariant mass plots do not simulate well at values far from Z boson mass.

To remove this unwanted background, selection cuts can be applied to only select leptons from events that meet the criteria of leptons that decay from the Z boson. The 'standard' cuts that meet this criteria are two leptons detected from each event, which are opposite charge and the the same flavour.

Leptons produced by Z boson decay are usually isolated from other particles produced in proton-proton collisions. However, leptons from background processes such as bottom quark decay are accompanied by jets of other various particles. Therefore, a variable called transverse momentum cone which contains a sum over transverse momentum of all tracks contained within a cone of half-width ΔR around the lepton direction can be used to identify this. This is known as an isolation variable and can be used to make a cut to reduce background sources of leptons produced in Z decay.

III. EXPERIMENTAL METHOD AND RESULTS

Investigating the transverse momentum distribution, figure 2, for leptons from proton-proton collisions reviled a substantial difference between ATLAS data and Monte Carlo at lower transverse momentum, figure 3.

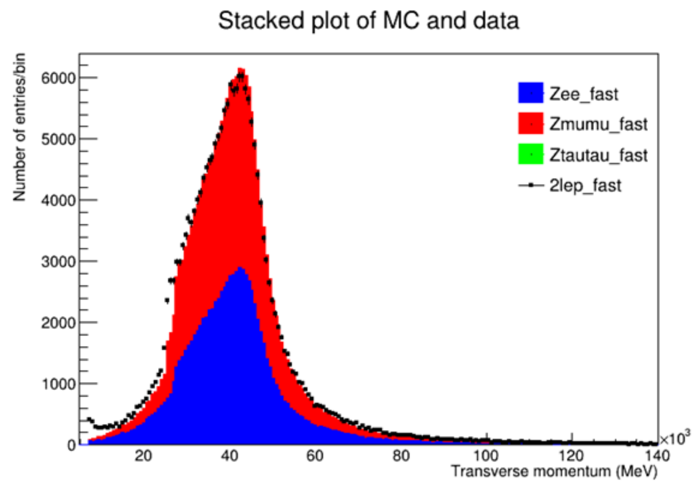

FIG. 2. Stacked transverse momentum plot of ATLAS data(black) and Monte Carlo(red and blue). It peaks around 45GeV as each particle takes half the energy of the Z boson.

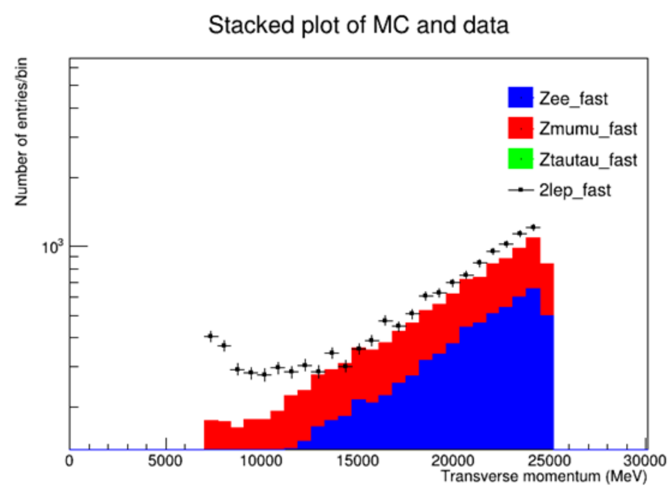

FIG. 3. Low transverse momentum plot showing the contribution from bottom decay and jets as the data is greater than the simulated.

A transverse momentum cut was made to remove this as seen in table 1, this cut was made by referencing figure 2 and looking where the data and Monte Carlo start to match at low transverse momentum. Transverse momentum cone cut was determined by comparing ATLAS data and Monte Carlo for invariant mass plots. Various ranges of transverse momentum cone were applied and the most closely agreeing range was selected. The invariant mass plot for Monte Carlo is only simulated well between 60 and 120GeV, therefore this cut was used.

Table 1 provides positive feedback that our cuts remove a substantial amount of our background, the remaining background will be accounted for in our systematic uncertainty.

From equation (2), the selected events($N^{selected}$) is read from the integral of the histogram of transverse mo-

Cut Variable	Parameter	% background reduced
Lepton No. in event	2	N/A
Lepton Charge	Opposite Charge	N/A
Lepton Flavour	Same Flavour	N/A
Transverse Momentum	$P_T \geq 25GeV$	7.36
Invariant mass	$60 \leq M_{inv} \leq 120GeV$	70.95
P_T cone(R=0.3)	$\leq$ 3GeV	0.91

TABLE I. Table of selection cuts to select leptons only from Z boson decay and reduce background. Shows percentage of background reduced after each cut.

mentum against number of events per bin. The events recorded were 4.35×10^6 and 4.83×10^6 for electrons and muons respectively. The efficiency is number of selected events divided by all generated events in the relevant sample which was provided by the python script and is calculated to be 0.44 and 0.50 for electrons and muons respectively. The number of background events were calculated from a data driven method. This method consists of selecting leptons from events that should not come from Z boson decay, for example, different flavour and same charge. After collecting all the events from 3 different type of events the background estimate($N^{background}$) for ATLAS data and Monte Carlo were calculated, and after subtracting the latter, the number of background events was 6.75×10^4 for both electrons and muons. However, from invariant mass plots of same flavour, same charge there was a Z boson peak. This is from signal contamination. The contamination is from Bremsstrahlung radiation of one of the leptons, specifically the electron as it has a small mass. This is when an electron emits a gamma ray which decays into an electron positron pair and the positron carries the majority of the energy so it is misidentified as a electron positron pair which is created from Z boson decay. Monte Carlo also simulates this contamination therefore when subtracted the effect is mostly cancelled out.

This produced a cross section for Z boson decay to opposite charge electrons as $\sigma_Z^{e^+e^-} 1.930 \pm 0.001(stat.) \pm 0.058(syst.) \pm 0.033(lumi.)nb$, and for muons $\sigma_Z^{\mu^+\mu^-} 1.93 \pm 0.001(stat.) \pm 0.066(syst.) \pm 0.033(lumi.)nb$.

A. Uncertainties

The statistical uncertainty was calculated from the Poisson distribution of the number of events, $\sqrt{N}$ and propagated through equation (2). Systematic uncertainty is a result of unaccounted background and disagreements between Monte Carlo and real data. The estimation of this was done by varying transverse momentum and transverse momentum cone. This method takes into consideration all the unaccounted background and the variance in the cross section lets up calculate the bias it creates. The transverse momentum cut was increased from the standard 25GeV, every 5GeV, until 55GeV which is the end of the transverse momentum peak. The transverse momentum cone cut was varied less than 2,3,4 and 6GeV. For both of these the cross section was recalculated for each new cut and the standard deviation was calculated to gt the systematic uncertainty. Transverse momentum was the dominant uncertainty over transverse momentum cone. The integrated luminosity uncertainty was given as 1.7% and this was propagated through (2).

IV. CONCLUSION

The values of production cross section for the two lepton groups presented give a ratio of $R_Z = \sigma_Z^{e^+e^-}/\sigma_Z^{\mu^+\mu^-} = 0.998 \pm 0.001(stat.) \pm 0.045(syst.) \pm 0.024(lumi.)nb$ [4]. This ratio can be used as evidence for lepton universality, and therefore the standard model. The cross sections have an average error of 5% which is within one standard deviation of a previously preformed experiment at ATLAS suggesting our method has produced a reasonable result [5].

An improvement of systematic errors could be achieved by investigating the cross section by varying invariant mass cuts.

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