Search for new physics in tri-muons event with ATLAS, based on ATLAS open data

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A search for physics beyond the standard model, in final states with three muons events, is performed using 10 fb^{-1} of proton-proton collision data using ATLAS Open Data. No significant excess of events beyond Standard Model is observed. Exclusion limit is set on the cross-section times efficiency ($\epsilon\sigma$).

I. INTRODUCTION

The Standard Model of particle physics (SM) which provides the remarkable description of the properties of elementary particles possess two main classes of particles: bosons and fermions and a $SU(3) \times SU(2) \times U(1)$ gauge group, where the fermions have three generations of quarks and leptons[1]. All the SM particles interact via three fundamental forces: the electromagnetic, the weak, and the strong interaction, with the first two being unified in the electroweak force. It is confirmed after the discovery of Higgs boson in 2012 [2] at Large Hadron Collider, CERN.
At the same time, there remain questions about the large hierarchy between the Planck and the electroweak scales, a more "natural" explanation for the Yukawa mass terms of the fermions, origin of dark matter etc.—questions that are not answered within the SM. Over the years, many models purporting to go "beyond the SM" (BSM) have appeared in the literature—a common feature of these models is the presence of some new physics around the TeV scale either in the form of new heavy vector, scalar, or fermion resonances [3].

Models with extra gauge symmetry are well-motivated extensions of the Standard Model. The extended model predicts the existece of the heavy neutral and heavy charged gauge bosons. In this paper, we analyse the ATLAS Open data in search of charged heavy gauge boson, $W^{'}$. The $W^{'}$ decays to produce SM $W^{\pm}Z$ diboson. In the SM the $W^{\pm}Z$ diboson production arises from two vector bosons radiated by quarks or from the decay of the virtual W boson into a $W^{\pm}Z$ pair, the latter of which involves the a triple gauge coupling.

The study of the diboson production is an important part of the physics programme in hadron collisions as it represents an important test of the electroweak sector of the SM. In particular, the $W^{\pm}Z$ diboson production arises from two vector bosons radiated by quarks or from the decay of a virtual W boson into a $W^{\pm}Z$ pair, the latter of which involves a triple gauge coupling.

II. ATLAS DETECTOR

ATLAS is a multipurpose detector with a forward-backward symmetric cylindrical geometry and nearly 4 coverage in solid angle. It consists of an inner tracking detector (ID) surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic (EM) and hadronic calorimeters, and a muon spectrometer (MS). The ID covers the pseudorapidity range $|\eta| < 2.5$. The muon spectrometer surrounds the calorimeters and includes three large superconducting air-core toroids. The field integral of the toroids ranges between 2.0 and 6.0 T m for most of the detector. The MS includes a system of precision tracking chambers and triggering chambers.

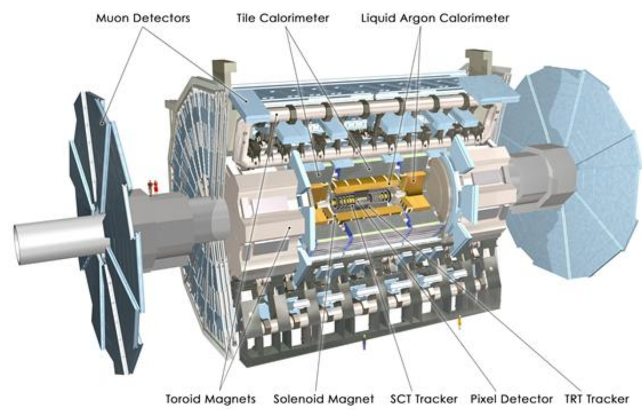

FIG. 1. ATLAS Detector at CERN [4]

III. MUON SIGNAL

Muons are negatively charged spin haif particles having charge $1e^{-}$, and they respond to the electroweak force and not the strong force. But they are much heavier in mass compared to the electrons. Most other particles, unlike muons, lose all of their energy in the calorimeter and are unable to reach the muon spectrometer. Without the jumble of signals left by other particles, muons leave very clean tracks for physicists to analyse.

IV. DATA AND SIMULATION

A. Data

The 13 TeV ATLAS Open Data[5] events belong to 61 runs from the first four periods of the 2016 pp data-taking and contain approximately 270 million of collision events. Only events for which all relevant subsystems were operational were considered. After applying quality criteria for the beam, data and detector, the publicly released dataset corresponds to an integrated luminosity of $10.06 \pm 0.37 fb^{-1}$[6]. The events reconstruction is affected by multiple inelastic pp collisions in a single bunch crossing and by collisions in neighbouring bunch crossings, referred to as "pile-up". The number of interactions per bunch crossing in this data set ranges from about 8 to 45.
Our data under analysis consists of at least two leptons (electrons or muon). The muon candidates are reconstructed by combining tracks reconstructed in both the inner detector and muon spectrometer (MS). The muon candidates are selected if they have a transverse momentum above 7 GeV and pass the "loose" identification requirements defined in Ref.[7]. To reduce the contributions from the non-prompt leptond (e.g. fromm semileptonic b- or c-hadronn decays), photon conversions and hadrons. "loose" isolation requirements are applied to both the electron and muon candidates. Events with at least one electron or muon are selected with single-lepton triggers with either low p_T thresholds of 26 GeV and isolation requirements, or with higher thresholds of 50-60 GeV but with a loose identification criterion and without any isolation requirement. Corrections are applied to the MC samples to match the leptons' trigger, reconstruction and isolation efficiencies in data.

B. Signal models and simulation

The expected signal model is the BSM heavy gauge boson decaying to $WZ \to \mu\nu_\mu\mu^+\mu^-$. But in this analysis, we used the following signal characteristic.The Supersymmetric particles chargingo and neutralino decaying to WZ + $E_T^{miss} \to 3l + \nu$ with chargino mass 400 GeV and Neutralino mass 0 GeV. In the plot, it is written as BSM1. The Chargino have the similar signal characteristics to that of the BSM Charged gauge boson and the Neutralino are the lightest stable particle. The actual used signal events has large E_T^{miss} compared do the one shown in Fig:2. This is due to missing transverse energy from both neutrino and neutralino.

V. SELECTION

The analysis presented here is focused on implementing the selection criteria for $W^\pm Z \to \mu^\pm \bar{\nu_\mu} \mu^\pm \mu^\pm$ leptonic decays, where the Z boson decays into leptons and the

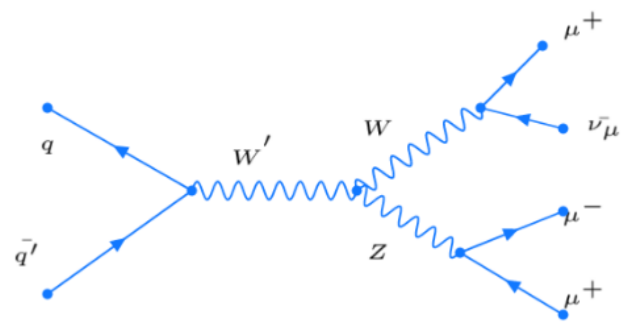

FIG. 2. Feynman diagram showing BSM charged gauge boson $W^{'} \to WZ \to 3\mu + \nu$[9]

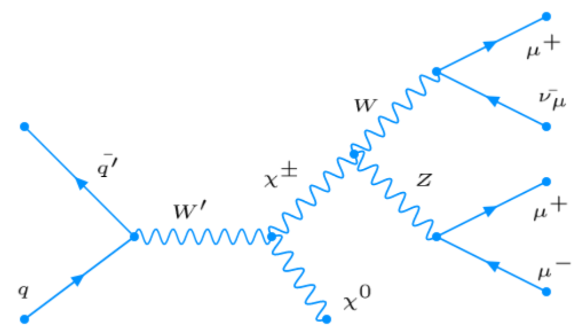

FIG. 3. Feynman diagram with $W^{'} \to \chi^\pm + \chi^0, \chi^\pm \to 3\mu + \nu$[9]

W boson decays into a muon and a muon neutrino. The selection is loosely based on the $W^\pm Z$ production cross-section measurements using $\sqrt{s} = 13$ TeV data collected in 2015 by the ATLAS experiment. Standard Object-selection criteria are applied, with a loose lepton P_T requirements and tight lepton identification criteria. The final event-selection criteria as stated in the ref.[8] are:

- Single-muon trigger satisfied;
- Exactly three muon with $p_T > 20$ GeV, at least one of them should have $p_T > 25$ GeV;
- Candidate events are required to have at least one SFOS-pair of muons with an invariant mass that is consistent with the nominal Z-boson mass(m_Z = 91.18 GeV) to within 10 GeV, considered to be the Z-boson candidate;
- Both the missing transverse momentum E_T^{miss} and the transverse mass of the W candidate M_T^W are required to be larger than 30 GeV.

The invariant mass of the Z boson is reconstructed from the other two muons events that does not contribute

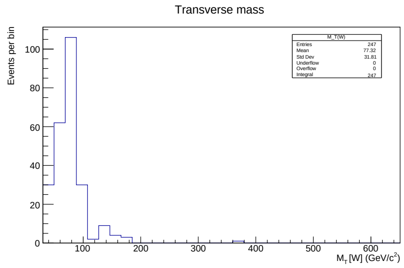

FIG. 4. Transverse mass of W boson

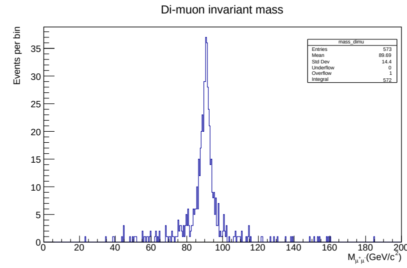

FIG. 5. Invariant mass of Z Boson

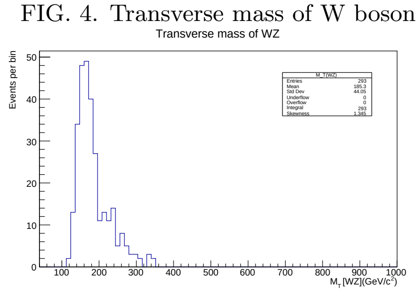

FIG. 6. Transverse mass of WZ diboson

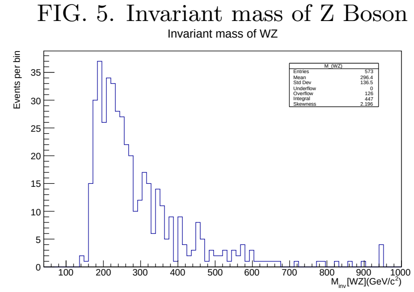

FIG. 7. Invariant mass of WZ boson

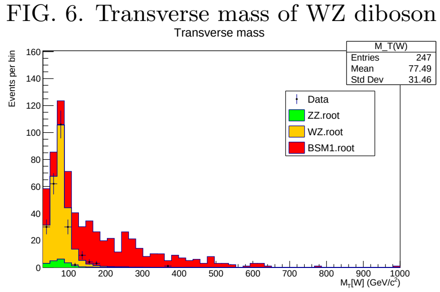

FIG. 8. Transverse mass plot of Data with MC Samples and BSM1 sample for W boson

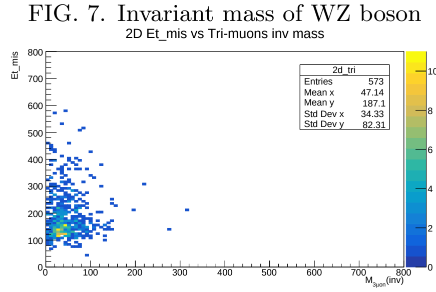

FIG. 9. 2D Histogram plot for tri-muons invariant mass versus E_T^{miss}

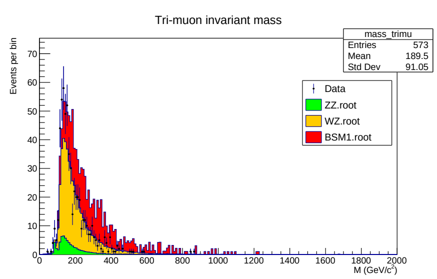

FIG. 10. Invariant mass of tri-muon plot in for the same scaling factor as transverse mass of W boson

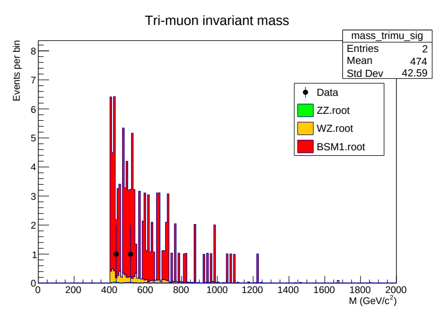

FIG. 11. Invariant mass plot in the signal region

to the W boson. The transverse mass of the WZ boson is calculated using the following expression as in ref. [10]:

$$\mathrm{M}_T^{WZ} = \sqrt{\left(\Sigma_{l=1}^{3}(p_T^l + E_T^{miss})\right)^2 - \left[\left(\Sigma_{l=1}^{3} p_x^l + E_x^{miss}\right)^2 + \left(\Sigma_{l=1}^{3} p_y^l + E_y^{miss}\right)^2\right]}$$

For the reconstruction of the invariant mass of WZ diboson. We found the η of the neutrino from the relation in the relativistic domain.

$$M^2 = 2p_{T_1}p_{T_2}\left(cosh(\eta_1 - \eta_2) - cos(\phi_1 - \phi_2)\right) \qquad (1)$$

For the case $W \rightarrow \mu + \bar{\nu_\mu}$, the η of the neutrino is calculated as for given mass of W boson.

$$\eta_{\nu_\mu} = \eta_\mu \pm cosh^{-1}\left(\frac{M_W^2}{2p_{T_\mu}E_T^{miss}} + cos(\phi_\mu - \phi_{\nu_\mu})\right) \quad (2)$$

Once, we know four momentum of all the final states particles, we can easiy construct the invariant mass.

VI. BACKGROUND ESTIMATION

Monte Carlo simulated events are used to estimate the contribution from the background processes. The main background events are from the WZ and ZZ dibosons. The contributions from the Z+jets events is very small. In particular, events from ZZ production survive the current event selection either because one muon fall outside the fiducial volume or because it falls in the fiducial acceptance of the detector but is not identified.

VII. SYSTEMATIC UNCERTAINTIES

The systematic uncertainties in the signal and backgrounds include those due to the limited numbers of simulated events and to the measurement of integrated luminosity. Experimental uncertainties arising from the trigger efficiencies, lepton identification and reconstruction procedures, and the energy calibration of leptons. Potential mismodelling by the MC simulations of the WZ, ZZ and Z+jets back-grounds is quantified by comparing the nominal against alternative simulated samples and PDF sets.

VIII. RESULTS

TABLE I. MC Sample Fractions

MC Sample	Events	Total	Fraction
WZ	254.6		92.8%
		274.2	
ZZ	19.6		7.2%

We defined a scaling of the MonteCarlo histograms that matches for the transverse mass of the W boson as shown in Fig:8. The MC samples fraction in contributing the data in the control region were determined calculating the number of events which is shown in TABLE I.

The obtained scaling from the transverse mass of the W-boson was applied to the invariant mass of the tri-muons events. We defined a control region that has rich background events as in equation 3 and a signal region that has high signal or events from the BSM $W^{'}$. The

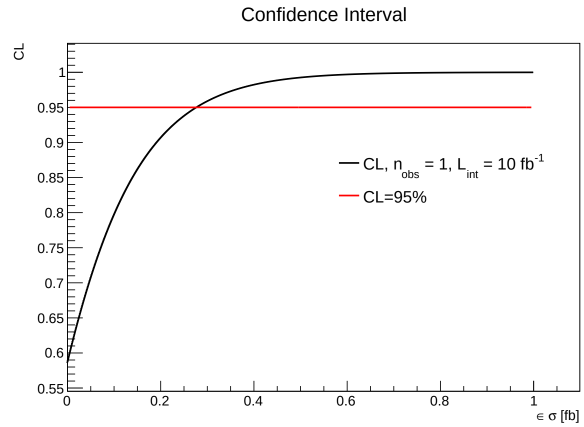

FIG. 12. Confidence Interval Plot

control region is defined on the basis of the E_T^{miss} and the invariant mass of the tri-muons events ($M_{3\mu}$) as shown in the appendix.

$$\begin{aligned} 30GeV \leq E_T^{miss} &\leq 80GeV \\ 95GeV \leq M_{3\mu} &\leq 400GeV \end{aligned} \quad (3)$$

whereas the signal region is:

$$\begin{aligned} E_T^{miss} > 80GeV \\ M_{3\mu} > 400GeV \end{aligned} \quad (4)$$

In the signal region, we observed two events and based on Bayes theorem [11], we are able to set limit on $\epsilon\sigma$ The obtained constrain was $\epsilon\sigma$ < 0.25 fb for Integrated luminosity $10fb^{-1}$. In the calculation of the confidence, we used tri-muon invariant mass because the invariant mass of the signal events has large overflow of the events. In overflow of the events in case of data is shown in Fig:7. The overflow of events was mainly due to the singularity appearing in the argument of $cosh^{-1}$.

IX. CONCLUSION

We cannot use the invariant mass of WZ diboson due to large overflow of events. The transverse mass of WZ diboson resemble with the background only hypothesis. So, we decided to use the invariant mass of the tri-muons events. We did not observe any significant excess of events over the background only hypothesis but we are able to put a constrain on efficiency times cross-section.

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Appendix A

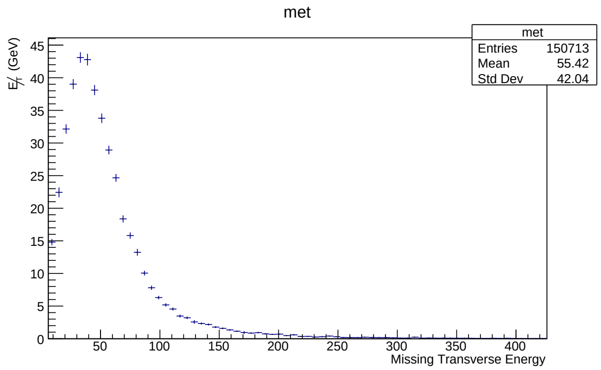

FIG. 13. Missing transverse energy plot for WZ

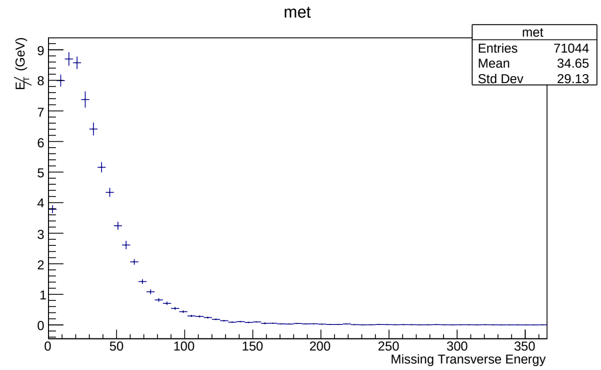

FIG. 14. Missing transverse energy plot for ZZ

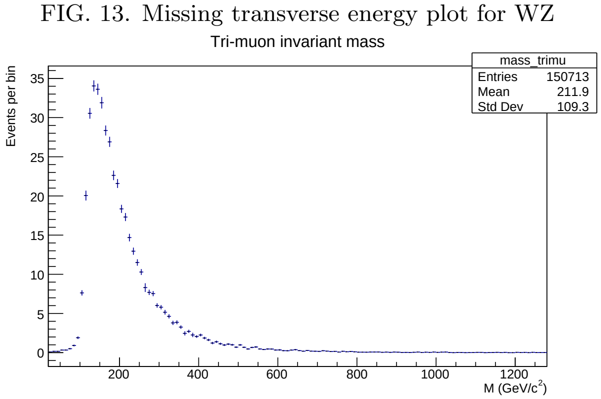

FIG. 15. Invariant mass of tri-muons mass for WZ

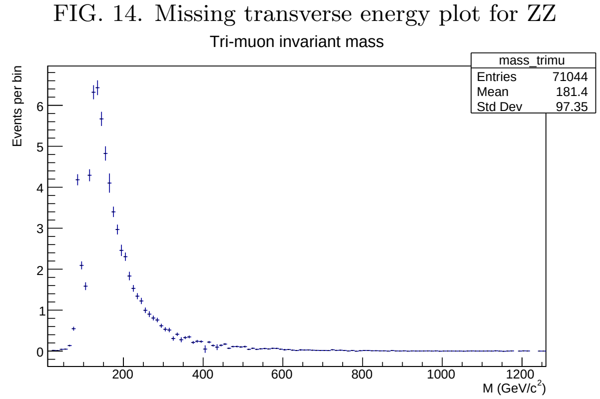

FIG. 16. Invariant mass of tri-muons events for ZZ