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Search for Higgs boson on the ZZ decay channel

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Abstract. A search for the Standard Model (SM) Higgs boson decaying into two Z bosons was done using 13 TeV data from the ATLAS experiment. The ATLAS detector and the decay channel used are briefly explained. The methods used to reconstruct the events, analyse the data and normalise the background that were used in this search are discussed. The observed signal is consistent with the SM prediction with a low statistical significance.

KEYWORDS: LHC, Higgs, ATLAS

1 Introduction

1.1 The Higgs Boson

In the last five decades the SM has been successful in describing high energy physics interactions. The Higgs Mechanism is a fundamental part of the SM and is responsible for breaking the eletroweak symmemtry and allows us to explain the origin of the mass of the fundamental particles along with predicting the existence of a scalar boson, known as the Higgs boson. The Higgs boson is generally produced in the LHC, using proton-proton collisions with very high center of mass energy and detected by measuring its decay products. The Higgs Boson production cross-section and its possible decay channels and likehood depend greatly on the mass of this particle. However the cross-section for its production is much smaller than the cross section for most other processes that occurs during collisions at the LHC so it is hard to detect one of these particles and a large amount of data is needed to get any reasonable conclusion [1]. During our analysis we focused on finding the Higgs boson in a mass range around 125 GeV, using open-access proton-collision data made available by the ATLAS collaboration.

1.2 The ATLAS detector

The ATLAS detector was designed with a cylindrical symmetry to further optimize the on-going studies in High-Energy physics, including the Higgs boson over a wide mass range. ATLAS is equipped with several subdetectors to detect both the energy and momentum of a variety of particles and finally, reconstruct the dynamics of the collision. The momentum is measured by a inner tracking detector (ID), in a 2-T axial magnetic field provided by a superconducting magnet. The energies of electrons and photons are measured in an electromagnetic calorimeter (ECAL) surrounding the inner detector and magnet, while the energy of the of hadronic paricles is measured with the hadronic calorimeter (TileCal, HEC and FCal). Only energetic muons and the weakly interacting neutrinos pass it. Finally, the muon spectrometer surrounds the calorimeters. This spectrometer consists of superconducting magnets providing a toroidal field and a system of precision charged-particle detectors. For a full description of the detector see Ref.[2].

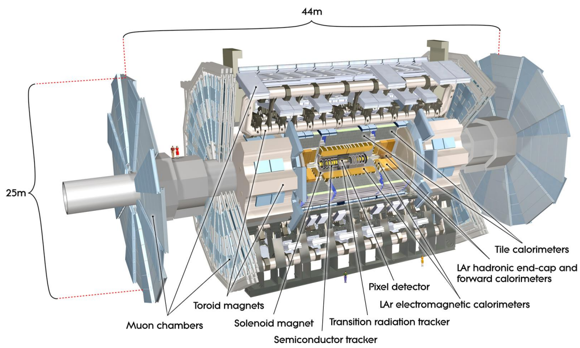

Figure 1. Schematic view of the ATLAS detector. Taken from [3].

1.3 Relevant variables

Here it is presented a list of the main variables which can be measured with the detector and are used in this analysis.

- p_T : transverse momentum;
- E_T^{miss} : missing transverse energy - energy missing from the transverse direction that should be present due to conservation of momentum and energy;
- M : invariant mass;
- N : multiplicity of objects (example: N_e is the number of electrons)

1.4 The H $\rightarrow$ ZZ $\rightarrow$ $\ell\ell\ell\ell$ decay

To find the SM Higgs boson, we look for the final products of its decay. One of these decay channels is H $\rightarrow$ ZZ $\rightarrow$ $\ell\ell\ell\ell$, where $\ell = e$ or μ, and it is the one we focused on during our analysis. The signal created by this decay is one of the clearest as it produces four isolated leptons which

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are easier to identify and whose proprieties are easier to measure. However, since only a small fraction of Higgs bosons decay in two Z bosons and only a small fraction of Z bosons (approximately 7% [4]) decay into eletrons and muons, the rate of this process is low. This search for the Higgs Boson is done by selecting two pairs of isolated leptons, each being comprised of two leptons of the same flavour but opposite charge. These two pairs are then used to reconstruct the event and the Higgs boson candidate.

2 Event Reconstruction

In order to reconstruct and characterize the events, an identification of several objects is needed, such as muons, electrons and neutrinos (identified by the missing transverse energy, E_T^{miss}). The electrons were reconstructed from the electron energy deposits in the electromagnetic calorimeter (ECAL), while the muons were reconstructed from the energy deposits and the trajectories provided by the muon spectrometer, which uses a strong magnetic field. The reconstructed electrons and muons were then given to us in the data set which we used for the analysis. Knowing the energies and momenta of the four final leptons allows us to fully reconstruct the event. To do so, we need two pairs of leptons with the same flavour and opposite charge and as such we have four distinct possibilities for our decay: $e^+e^-e^+e^-$, $\mu^+\mu^-e^+e^-$, $e^+e^-\mu^+\mu^-$ and $\mu^+\mu^-\mu^+\mu^-$. If the event is indeed a Higgs boson decay through this channel then each pair would have been created by a Z boson decay. As such the dilepton invariant mass of each pair is calculated and the reconstructed particle with a dilepton invariant mass closest to the real mass of a Z boson is designated Z_1, while the particle reconstructed from the other pair is called Z_2. To obtain the mass of our Higgs boson candidates we calculate the invariant mass of the four leptons.

3 Experimental procedure

Simulations of signal and background processes are produced using Monte Carlo methods and are used in our analysis to optimize our analysis. These simulations allow us to estimate the number of Higgs boson events in the data as well as the number of background events. The signal simulations are used to compare our measured signal with what was expected within the SM.

Trigger

Due to the large number of interactions taking place in the ATLAS detector, there are established triggers to several detectors in order to trim out unwanted events and maximize the registered data on the pretended interactions. This is usually achieved by lower-limiting the transverse momenta for the leptons, whether it being on a isolated or a pair of leptons. For this 13 TeV data set we used the single-lepton trigger with a threshold of 25 GeV.

Event selection

The events are then are subjected to more selection criteria in order to improve the signal to background ratio. Signal events are characterised by the production of two Z bosons, one of which is real and the other virtual, which then decay into a pair of leptons each. We are limiting our search for the Higgs Boson to the 125 GeV mass region therefore these four leptons produced should have a invariant mass of about 125 GeV in order to be considered as a possible Higgs boson event.

Table 1. Criteria for the event selection.

Variable	Selection [GeV]
$p_T(\ell_1)$	>20
$p_T(\ell_2)$	>15
$p_T(\ell_3)$	>10
$p_T(\ell_4)$	>7
$M(Z_1)$	[50, 130]
$M(Z_2)$	[15, 80]
N_ℓ	≥ 4
N_{jet}	≤ 3

Since jets are not expected to be produced in this decay channel, only events with a small number of jets are selected in order to reduce the $t\bar{t}$, $t\bar{t}Z$ and Z+jets backgrounds. Since there are no neutrinos produced in this decay channel, one would also expect a low missing transverse energy. However, no selection is done based on this parameter as doing so reduced the signal significance of our final result.

4 Background estimation

The simulations for the various background processes are not normalised to the luminosity of the data used. As such, some normalisation procedure is needed so that the simulated and experimental data can be compared. The dominant background for this decay channel is the production of two Z bosons. To normalise it, we selected a control region in which we knew there was no contribution from the Higgs boson signal and other backgrounds were reduced as much as possible. This was done by selecting a region such that the invariant mass of the four leptons was less than 100 GeV. Figure 2 shows a representation of our control region before it was normalised. As it is possible to see, the simulation of the background has a similar shape to the distribution of the data points, but with a different scale.

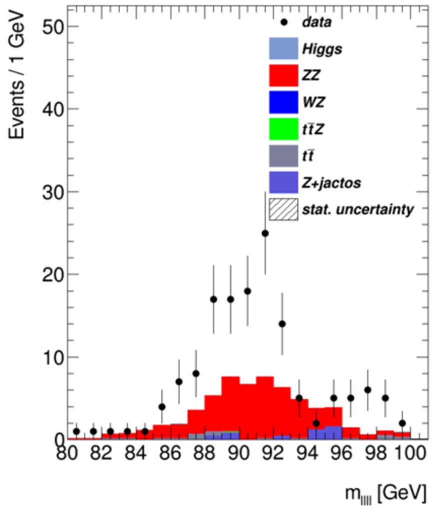

Figure 2. ZZ Background in the control region before normalisation.

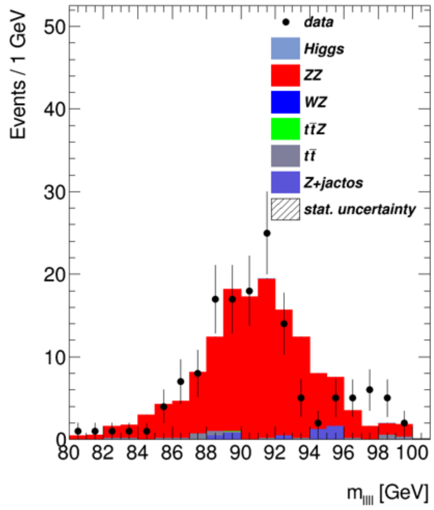

Figure 3. ZZ Background in the control region after normalisation.

Table 2. Number of events per type in the control region before normalisation.

Type	Number of events
Z+jets	4.6 ± 1.8
$t\bar{t}$	3.5 ± 0.8
$t\bar{t}Z$	0.03 ± 0.01
WZ	0.00 ± 0.00
ZZ	53.5 ± 1.6
Higgs	0.15 ± 0.01
Data	147
Total Background	61.7 ± 2.5

Table 3. Number of events per type in the control region after normalisation.

Type	Number of events
Z+jets	4.6 ± 1.8
$t\bar{t}$	3.5 ± 0.8
$t\bar{t}Z$	0.03 ± 0.01
WZ	0.00 ± 0.00
ZZ	139 ± 4
Higgs	0.15 ± 0.01
Data	147
Total Background	147 ± 5

The expected number of ZZ events present in the data is estimated after subtracting the contributions from the other simulated samples. This value was then divided by the number of ZZ events in the simulated sample to obtain a scale factor of 2.59 ± 0.24. The ZZ background in the simulation was multiplied by this value so that it better described the data, as can be seen in figure 3 and table 3.

5 Results and Conclusions

To check for the presence of our signal, we selected a mass region (invariant mass for the 4 leptons) where we expect the Higgs Boson events (115-131 GeV).

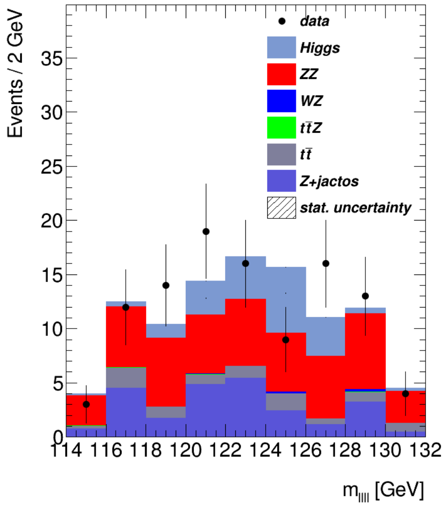

Figure 4. Selected Signal Region for calculation of signal significance and strength

Table 4. Number of events per type in the signal.

Type	Number of events
Z+jets	24.60 ± 5.10
$t\bar{t}$	9.2 ± 1.4
$t\bar{t}Z$	0.21 ± 0.03
WZ	0.46 ± 0.21
ZZ	47.5 ± 2.4
Higgs	19.4 ± 1.5
Data	106
Total Background	101 ± 6

Then to the number of selected data events (N) in this region, we subtracted all the background events (B) and divided by the uncertainty of the number of events. The estimated number of Higgs Boson events in the data is S=24.05 ± 11.83.

$$\frac{S}{\sigma_S} = \frac{N - B}{\sigma_N + \sigma_B} \tag{1}$$

The signal significance, gives us a good measure of whether the Higgs signal in the data is a statistical fluctuation or not. A 2.34 σ signal significance was obtained. This signal significance does not allow to say with certainty if this excess of events is due to the Higgs boson. Another useful quantity is the signal strength, which is the ratio of the theoretical and experimental cross-sections. In this case, this ratio is equal to the ratio between the number of measured Higgs events and the SM simulation for the Higgs boson.

$$\mu = \frac{\sigma_{Experimental}}{\sigma_{Theoretical}} = \frac{N_{Experimental}}{N_{Theoretical}} \tag{2}$$

A 1.2 ± 0.6 signal strength was obtained. If this signal was due to the Higgs boson then the value obtained for the signal strength is consistent with the SM prediction.

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