Search for the Higgs boson to 4 leptons through new gauge bosons

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Abstract. The $H \rightarrow ZZ^{(*)} \rightarrow 4l$ channel has long been known to be the dominant discovery channel for the Standard Model (SM) Higgs boson with the ATLAS detector, thanks to its clean signature of 4 isolated leptons. However, some Hidden Valley (HV) scenarios predict the existence of a new sector with Higgs and gauge bosons (Z'). The Higgs boson could therefore decay to a pair of Z' through the mixing between the Standard Model (SM) and the HV sectors. In this study, prospects for a Higgs discovery in the decay channel $H \rightarrow Z'Z' \rightarrow 4l$ (where l can either be an electron or a muon) is being investigated. This channel has both a clean signature and a potentially large branching ratio for a low mass Higgs boson ($m_H < 200$ GeV/c^2). The Z' bosons in the present model can have a mass as low as 5 GeV/c^2, and decay preferably to SM fermions (leptons or light quarks) with a very narrow width. The $H \rightarrow Z'Z' \rightarrow 4l$ channel can be explored a similar way to the standard $H \rightarrow ZZ^{(*)} \rightarrow 4l$ channel, by changing the constraints on the dilepton invariant mass. Based on the study of 9 benchmark points, we developed a new algorithm to select our signal and reject the SM background, by constraining the two dilepton pairs to have the same mass within a certain window. The dominant backgrounds are also studied. Perspectives on this new approach with the ATLAS experiment are presented.

1. Introduction

The Higgs boson is considered as the last missing piece of the Standard Model (SM) of Particle Physics. In the low-mass region, the Higgs boson is mostly searched for through its decay to two photons ($H \rightarrow \gamma\gamma$) or to four leptons through Z bosons ($H \rightarrow ZZ^{(*)} \rightarrow 4l$): these channels suffer from a relatively low branching ratio (BR) but have a very clean experimental signature. Recent results from the LHC experiments ATLAS [1] and CMS [2] in these channels seem to indicate the observation of a Higgs-like new particle at a mass of about 126 GeV/c^2 [3, 4]. This work is a search for a Higgs boson decaying to four leptons through new light gauge bosons ($H \rightarrow Z'Z' \rightarrow 4l$), with the ATLAS detector. The leptons considered here are electrons and muons. We will focus on the low-mass region ($m_H < 200$ GeV/c^2). Although in this study we consider all final states (4 electrons, 4 muons, 2 electrons plus 2 muons), we will present results concerning the 4-muon channel (4μ) only.

2. Theoretical framework

2.1. Abelian Hidden Sector model

Some Abelian Hidden Sector models [5] predict the existence of new Higgs and gauge bosons (Z'). The process $H \rightarrow Z'Z'$ is made possible through the kinetic mixing between the SM and Hidden sectors. The mass of the new gauge boson Z' is not constrained by the model and the particle can be as light as a few GeV/c^2. It is weakly coupled to SM fermions so that the model is compatible with previous experimental data (from the LEP experiments), but the decay $Z' \to ll$ is allowed with a possibly large BR. These arguments make the search for a Higgs boson decaying to 4 leptons through a pair of Z' bosons relevant in the low-mass region: it benefits from the clean experimental signature of the "golden" channel and is accessible with minimal changes to the standard $H \to ZZ^{(*)} \to 4l$ analysis.

Although this study mainly focuses on one particular model, it should be noted that the search for low-mass resonances is also motivated by other models, such as "dark Z" models [6].

2.2. Signal event simulation

For this analysis, events were simulated with the MadGraph event generator [7], interfaced with Pythia [8] for parton showering, and then passed through the simulation of the ATLAS detector [9]. The event generation was made consistently with the Abelian Hidden Sector model of Ref. [5]. Several benchmark points were considered, as shown in Table 1. For the first points (light H and Z'), we see that we can expect to see several hundreds of $H \to Z'Z' \to 4l$ events in the data already collected in 2011 (about 5 fb^{-1}), or to exclude the model.

Table 1. Benchmark Points generated with MadGraph and the corresponding cross-sections (σ) times branching ratio (BR) at $\sqrt{s} = 7$ TeV.

H mass [GeV/c^2]	120	120	120	130	130	130	150	250
Z' mass [GeV/c^2]	5	20	50	5	20	50	50	100
$\sigma(gg \to H) \times BR(H \to Z'Z' \to 4l)$ [pb]	1.61	1.20	0.70	1.27	0.95	0.54	0.34	0.0004

For each point, 30000 events were generated. These events are used to optimize the analysis algorithm, in particular maximize the signal event selection and the background rejection. This analysis is based on events simulating 7-TeV collisions in the conditions of the 2011 data-taking period.

2.3. Backgrounds

In this study, the irreducible background is composed of events with 4 leptons in the final state. The dominant one is the direct $pp \to ZZ^{(*)} \to 4l$ production, but other processes can produce this final state (in particular events containing J/ψ mesons). There is also a background which can be reduced with the particle identification. These are events containing leptons and jets faking leptons, such as the processes $(Z \to ll)$+jets and $t\bar{t}$.

Besides this, there is a non-physical background coming from the final state topology: when selecting 4 leptons, several combinations are possible and the "wrong" combinations form the combinatorial background. We will see that this analysis also aims at reducing the contribution of this background.

3. Experimental setup

3.1. The LHC and the ATLAS Detector

The ATLAS detector [1] is a multi-purpose detector installed at the LHC[1], 100 m underground. The detector is composed of various sub-detectors. Going outwards from the beam-line, the sub-detectors are the Inner Tracking Detector (ID), the Electromagnetic (EM) calorimetry system,

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[1] The Large Hadron Collider (LHC) is a proton-proton collider located at CERN, in Switzerland. It has provided $p-p$ collisions at a center-of-mass energy $\sqrt{s} = 7$ TeV in 2010 and 2011, and at $\sqrt{s} = 8$ TeV since 2012.

the Hadronic calorimetry system, and the Muon Spectrometer. A complete description of the ATLAS detector and its components can be found in Ref. [1].

3.2. Muon reconstruction

Muons in the ATLAS detector are reconstructed primarily from the tracks they leave in the trackers (ID and MS). The magnetic fields allow a precise measurement of the particle momentum. In order to maximize the acceptance of the analysis, three types of reconstructed muons are considered:

- combined: from a track in the ID and a matching track in the MS;
- standalone : from a track in the MS only; and
- calorimetric : from the energy deposit in the EM calorimeter.

4. The $H \rightarrow Z'Z' \rightarrow 4\mu$ analysis: optimization of analysis algorithm

4.1. Event pre-selection

Given the huge amount of data provided by the LHC and recorded by ATLAS, an event pre-selection is needed. The pre-selection is aimed at maximizing the integrated luminosity by removing luminosity blocks[2] with detector defects or mis-behavior. To ensure that a hard event took place, only events with at least one reconstructed collision vertex with three associated tracks are kept. Finally, and most importantly, the selection is made on the high-level trigger system. For the 4μ final state, it is required that the events fired a single or di-muon trigger. Details about the triggers in this search can be found in Ref. [10].

4.2. Four-muon events

Among the pre-selected events, we select events with 4 muons, by applying several cuts on the particle identification, kinematics (transverse momentum p_T, pseudo-rapidity η), track quality and projectivity of the muon candidates. All possible quadruplets of leptons are kept at that stage. It is required that within a quadruplet, there are two pairs of same-sign, opposite-charge leptons. Additional kinematic cuts are applied, in particular the leading lepton should have $p_T > 20$ GeV/c, the subleasing lepton $p_T > 15$ GeV/c, the third lepton $p_T > 10$ GeV/c, and the fourth lepton $p_T > 7$ GeV/c, and that the reconstructed leptons match the triggered objects. A cut on the invariant mass of the lepton pairs is then applied, and is described in the next subsection as it is the central point of this analysis. The final cuts applied are separation between the leptons, calorimetric and track isolation, and the significance of the impact parameter. More details about this procedure can be found in Ref. [10] on which this analysis is based.

4.3. Optimization of the analysis: invariant mass cut

The cut on the invariant mass of the lepton pairs is optimized in order to maximize signal efficiency and background rejection. Unlike for a "standard" $H \rightarrow ZZ^{(*)} \rightarrow 4l$ analysis, where the known SM Z mass can be used as a constraint on the dilepton system, here we will use the fact that the two dilepton systems of a quadruplet must have the same mass within a window. This study is based on the benchmark points presented above, and the results will be shown for the points with a Higgs mass at 120 GeV/c^2 and a Z' mass at 5 GeV/c^2 and 50 GeV/c^2. The background considered is the dominant direct ZZ production.

In the following, we will consider quadruplets selected after the kinematic cuts mentioned above. In all cases, only one quadruplet was selected, which means in the 4μ case that there are

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[2] A luminosity block (LB) is a collection of events for which the data-taking conditions are constant. It is the unit of the Data Quality assessment.

two possible combinations for the dilepton pairs (combinatorial background). The lepton pairs within a quadruplet are labelled Z_1 and Z_2. The choice of the first and second pair is arbitrary.

Figure 1 shows the invariant mass distribution for the $H \rightarrow Z'Z' \rightarrow 4\mu$ signal (red solid line) and the ZZ background (black solid line) for the lepton pairs of the selected quadruplets.

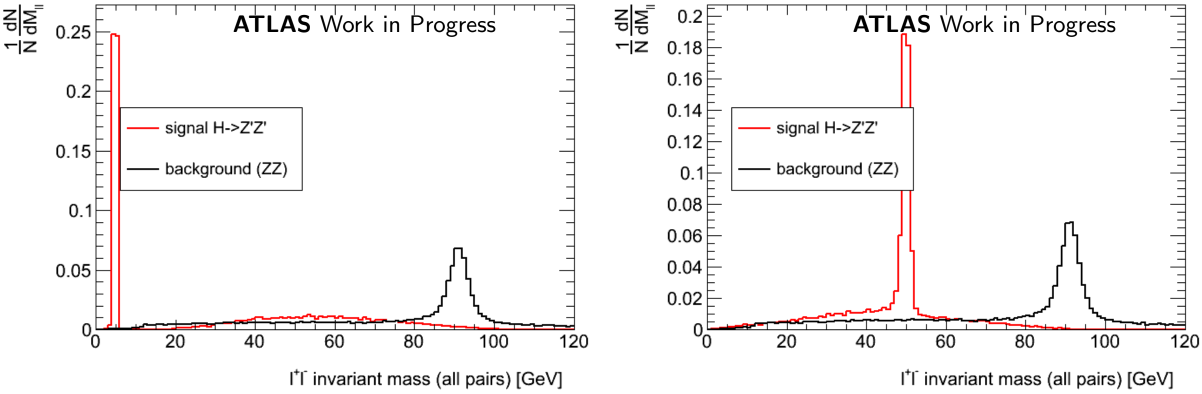

Figure 1. Dilepton invariant mass distribution for $H \rightarrow Z'Z' \rightarrow 4\mu$ signal (red) and ZZ background (black). All distributions are normalized to unity. The generated signal Higgs mass is $m_H = 120$ GeV/c^2. The generated Z' mass is $m_{Z'} = 5$ GeV/c^2 (left), and $m_{Z'} = 50$ GeV/c^2 (right).

It has to be noted that the signal distribution is narrower than the background distribution. Since all combinations are represented in this figure, each event provides 4 entries (2 pairs per quadruplet, and 2 possible quadruplet combinations). The combinatorial background is clearly visible in the tails of the distributions, adding an almost continuous distribution. The case of the combinatorial background is treated in section 4.4.

Figure 2 shows the invariant mass difference between the lepton pairs of the same selected quadruplets, again for the $H \rightarrow Z'Z' \rightarrow 4\mu$ signal (red solid line) and the ZZ background (black solid line).

The distribution is again sharper for signal than for background. Several cuts on $|M_{Z_1} - M_{Z_2}|$ are tested, from 5 GeV/c^2 to 50 GeV/c^2. In each case, the relative efficiency of the cut is measured, *i.e.* the ratio of the number of events after and before the cut. The measured efficiencies are represented by dots for the signal (red) and the background (black). For the lightest Z' (Fig. 2 (left)), the signal efficiency is 100% already for the smallest value of the cut. In the second case ($m_{Z'} = 5$ GeV/c^2, Fig. 2 (right)), the signal efficiency reaches 100% for larger values of the cut. In both cases, the background rejection is high for a cut at 5 GeV/c^2.

4.4. Combinatorial background

As mentioned earlier, the non-physical (combinatorial) background must also be removed. Figure 3 show the mass distribution of the same selected lepton pairs, for $H \rightarrow Z'Z' \rightarrow 4\mu$ signal. The contribution of the truth-matched pairs, *i.e.* muons coming from the same Z' identified using the Monte-Carlo truth information, is shown in red, while the combinatorial background is shown in blue ("wrong pairs").

This translates to the $|M_{Z_1} - M_{Z_2}|$ distribution as an almost continuous background, as shown on Fig. 4. It appears clearly that setting the cut at the lowest available threshold (5 GeV/c^2) will reduce the combinatorial background as well.

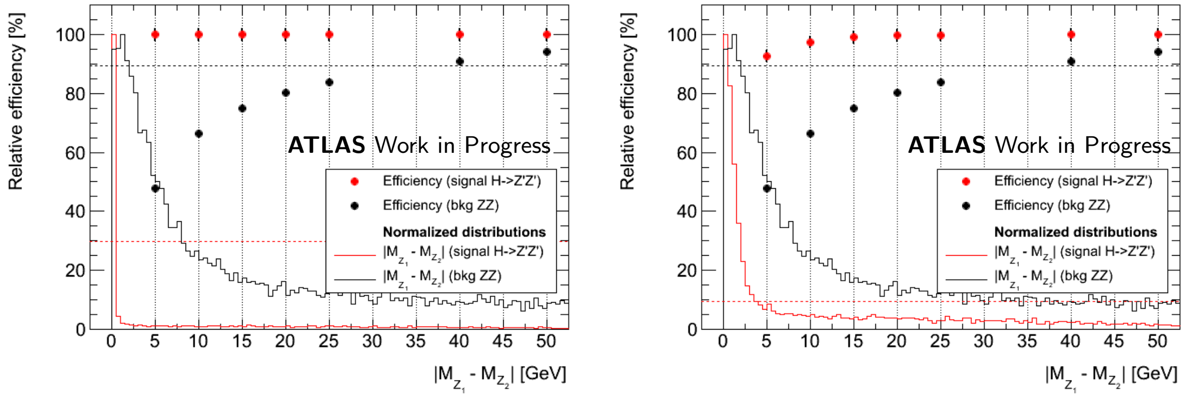

Figure 2. Difference between the invariant masses of the selected lepton pairs for $H \rightarrow Z'Z' \rightarrow 4\mu$ signal (red line) and ZZ background (black line), normalized to unity. The dots represent in each case the relative efficiency of the $|M_{Z_1} - M_{Z_2}|$ cut, for the cut threshold ranging from 5 GeV/c^2 to 50 GeV/c^2. The generated signal Higgs mass is $m_H = 120$ GeV/c^2. The generated Z' mass is $m_{Z'} = 5$ GeV/c^2 (left), and $m_{Z'} = 50$ GeV/c^2 (right).

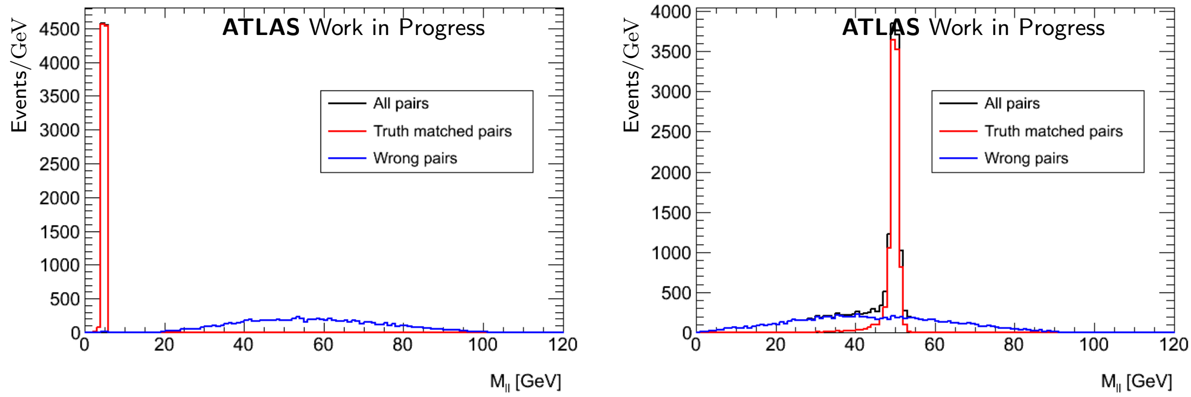

Figure 3. Dilepton invariant mass distribution for $H \rightarrow Z'Z' \rightarrow 4\mu$ signal. The truth-matched pairs are shown in red, while the combinatorial background is shown in blue (the black curve is the total). The generated signal Higgs mass is $m_H = 120$ GeV/c^2. The generated Z' mass is $m_{Z'} = 5$ GeV/c^2 (left), and $m_{Z'} = 50$ GeV/c^2 (right).

5. Conclusions

Using a set of simulated events, the analysis algorithm for $H \rightarrow Z'Z' \rightarrow 4l$ has been derived, based on the official standard $H \rightarrow ZZ^{(*)} \rightarrow 4l$ analysis of the ATLAS collaboration [10]. This includes in particular the definition of a cut which examines the difference between the invariant masses of the selected lepton pairs, in order to reject both the physical irreducible background (direct ZZ production) and the combinatorial background. The study presented here in the 4μ final state, has also been conducted for the other possible final states ($4e$ and $2e2\mu$) and lead to similar results. A cut value at 5 GeV/c^2 seems optimal in terms of signal efficiency and background rejection.

An extension of this study is in progress, to include a new model ("dark Z" model [6], with new gauge bosons of very low mass, from a few MeV/c^2 to a few GeV/c^2) and a new intermediate state ($H \rightarrow ZZ' \rightarrow 4l$). This requires a new approach of the analysis strategy, as the dilepton

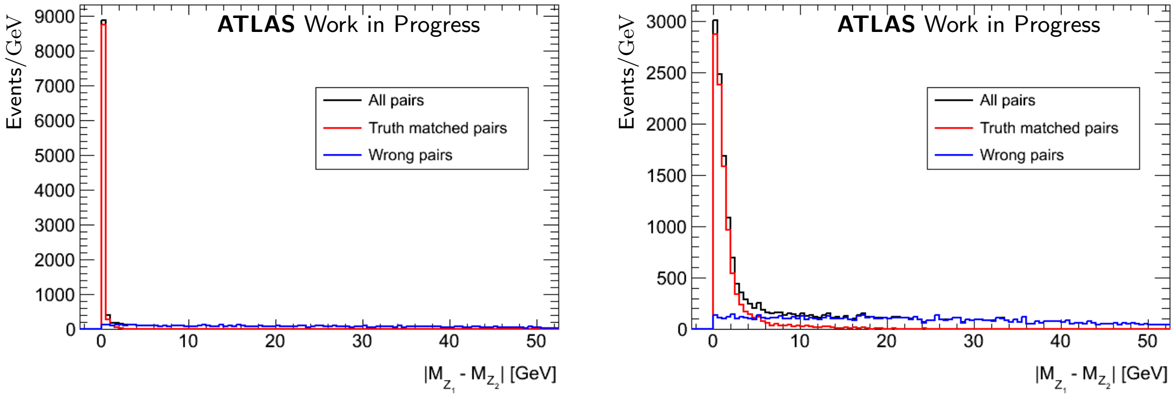

Figure 4. Difference between the invariant masses of the selected lepton pairs for $H \rightarrow Z'Z' \rightarrow 4\mu$ signal. The truth-matched pairs are shown in red, while the combinatorial background is shown in blue (the black curve is the total). The generated signal Higgs mass is $m_H = 120$ GeV/c^2. The generated Z' mass is $m_{Z'} = 5$ GeV/c^2 (left), and $m_{Z'} = 50$ GeV/c^2 (right).

systems will have a different invariant mass.

This analysis on simulated events shall be completed using the conditions of the 2012 data-taking period, before proceeding to the analysis of the combined 2011 and 2012 datasets. We estimate that with only the data already collected in 2011, corresponding to an integrated luminosity of about 5 fb^{-1}, several hundreds of events in the low mass region should already be produced. We therefore expect to draw an exclusion limit even before the end of the LHC run.

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