Search for a heavy Standard Model Higgs boson in the channel \(H \rightarrow ZZ \rightarrow \ell^+\ell^-q\bar{q}\) using the ATLAS detector

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**ABSTRACT**

A search for a heavy Standard Model Higgs boson decaying via \(H \rightarrow ZZ \rightarrow \ell^+\ell^-q\bar{q}\), where \(\ell = e, \mu\), is presented. The search is performed using a data set of \(pp\) collisions at \(\sqrt{s} = 7\) TeV, corresponding to an integrated luminosity of 1.04 fb\(^{-1}\) collected in 2011 by the ATLAS detector at the CERN LHC collider. No significant excess of events above the estimated background is found. Upper limits at 95% confidence level on the production cross section (relative to that expected from the Standard Model) of a Higgs boson with a mass in the range between 200 and 600 GeV are derived. Within this mass range, there is at present insufficient sensitivity to exclude a Standard Model Higgs boson. For a Higgs boson with a mass of 360 GeV, where the sensitivity is maximal, the observed and expected cross section upper limits are \(\sim 5–20\) times the SM prediction in the region of 200–600 GeV.

**1. Introduction**

The search for the Standard Model (SM) Higgs boson [1–3] is one of the most crucial goals of the LHC physics program. Direct searches at the CERN LEP \(e^+e^-\) collider have set a lower limit of 114.4 GeV on the Higgs boson mass \(m_H\) at 95% confidence level (CL) [4]. Searches by the CDF and D0 experiments at the Fermilab Tevatron pp collider have explored the Higgs boson mass range up to 200 GeV and exclude the region 156 GeV < \(m_H\) < 177 GeV [5].

The higher centre-of-mass energy (\(\sqrt{s}\)) of the LHC enables the search to be extended to much larger Higgs boson masses. Results from the 2010 run of the LHC, with \(\sqrt{s} = 7\) TeV and an integrated luminosity of about 40 pb\(^{-1}\), have excluded a SM-like Higgs boson with a cross section above \(\sim 5–20\) times the SM prediction in the mass range 200–600 GeV [6,7]. Although this mass range is indirectly excluded at 95% CL by global fits to SM observables [8], it is crucial to complement such indirect limits by direct searches; further, possible extensions to the SM can conspire to allow a heavy Higgs boson to be compatible with existing measurements [9]. If \(m_H\) is larger than twice the Z boson mass, \(m_Z\), the Higgs boson is expected to decay to two on-shell Z bosons with a high branching fraction [10–13]. In this Letter, we consider the Higgs boson mass range 200–600 GeV and search for a SM Higgs boson decaying to a pair of Z bosons, where one Z boson decays leptonically and the other hadronically: \(H \rightarrow ZZ \rightarrow \ell^+\ell^-q\bar{q}\) with \(\ell \equiv e, \mu\). This analysis uses 1.04 fb\(^{-1}\) of data recorded by the ATLAS experiment in the first half of 2011. The statistical sensitivity of the analysis is enhanced by treating events in which the hadronically-decaying Z boson decays to b quarks as a separate subsample. The largest background to this signal is \(Z + \text{jets}\) production, with smaller contributions from \(t\bar{t}\) and diboson (ZZ, WW) production.

**2. ATLAS detector**

The ATLAS detector [14] consists of several subsystems. An inner tracking detector is immersed in a 2 Tesla magnetic field produced by a superconducting solenoid. Charged particle position measurements are made by silicon detectors in the pseudorapidity range \(|\eta| < 2.5\) and by a straw tube tracker in the range \(|\eta| < 2.0\). The calorimeters cover \(|\eta| < 4.9\) with a variety of detector technologies. The liquid-argon electromagnetic calorimeter is divided into barrel \((|\eta| < 1.475)\) and endcap \((1.375 < |\eta| < 3.2)\) regions. The hadronic calorimeters (using liquid argon or scintillating tiles as active materials) surround the electromagnetic calorimeter and cover \(|\eta| < 4.9\). The muon spectrometer measures the deflection of muon tracks in the field of three large superconducting toroid magnets. It is instrumented with separate trigger \((|\eta| < 2.4)\) and high-precision tracking \((|\eta| < 2.7)\) chambers.

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3. Data and Monte Carlo samples

The data used in this search were recorded by the ATLAS experiment during the 2011 LHC run with pp collisions at $\sqrt{s} = 7 \text{ TeV}$. They correspond to an integrated luminosity of approximately 1.04 fb$^{-1}$ after data quality selections to require that all systems used in this analysis were operational. The data were collected using primarily single-lepton triggers with a transverse momentum ($p_T$) threshold of 20 GeV for electrons and 18 GeV for muons. The resulting trigger criteria are about 95% efficient in the muon channel and close to 100% efficient in the electron channel, relative to the selection criteria described below. Collision events are selected by requiring a reconstructed primary vertex with at least three associated tracks with $p_T > 0.4$ GeV. The average number of collisions per bunch crossing in this data sample is about six.

The $H \rightarrow ZZ \rightarrow 4\ell$ q$q$ signal is modelled using the POWHEG Monte Carlo (MC) event generator [15,16], which calculates separately the gluon and vector-boson fusion production mechanisms of the Higgs boson with matrix elements up to next-to-Monte Carlo (MC) event generator [15,16], which calculates separate cross section and decay branching ratio for the signal kinematic distributions. The total inclusive cross sections estimate the systematic uncertainty due to the modelling of the $\sim 450 \mu m$ of hadrons containing b-quarks. This is accomplished by considering the set of tracks associated with the jet and either reconstructing a secondary vertex from among them, or finding tracks that have a significant impact parameter with respect to the primary event vertex [47]. Information from both methods is combined into a single discriminating variable, and a cut applied that gives an efficiency of about 70% for identifying real b-jets (“b-tagging”), with a light-quark jet rejection of about 50.

Corrections are applied to MC events to account for various small differences between data and simulation observed and determined in a variety of samples, including $(J/\psi, \Upsilon, Z) \rightarrow \ell\ell$ and $W \rightarrow \ell\nu$. Quantities corrected include the average number of minimum-bias events per crossing, trigger and lepton identification efficiencies, and the lepton energy scale and resolution.

5. Event selection

The first step in the event selection is to reconstruct a $Z \rightarrow \ell\ell$ decay. Events must contain exactly two same-flavour selected leptons. The two muons of a pair must have opposite charge; this is not required for electrons because larger energy losses from bremsstrahlung lead to higher charge misidentification probabilities. The pair’s invariant mass must lie within the range 76 GeV < $m_{\ell\ell}$ < 106 GeV ($\approx m_{Z} \pm 15 \text{ GeV}$).

In addition to the $Z \rightarrow \ell\ell$ decay, the $H \rightarrow ZZ \rightarrow 4\ell$ q$q$ final state contains a pair of jets resulting from $Z \rightarrow q\bar{q}$ decay and no high-$p_T$ neutrinos. Thus, events must contain at least two jets and satisfy $E_{T}^{miss} < 50 \text{ GeV}$. The latter requirement reduces mostly background from tt production.

About 21% of signal events contain b-jets from $Z \rightarrow b\bar{b}$ decay, while a b-jet pair is rare (~2%) in the dominant $Z +$ jets background. Accordingly, the analysis is divided into a “tagged” subchannel, containing events with two b-tags, and an “untagged” subchannel, containing events with less than two b-tags. Events with more than two b-tags (approximately 3% of the data sample with $\geq 2$ jets) are rejected.

Further, the events are then required to have at least one candidate $Z \rightarrow q\bar{q}$ decay with dijet invariant mass satisfying 70 GeV < $m_{jj}$ < 105 GeV in order to be consistent with a Z boson decay. This cut is asymmetric around the Z boson mass since there are non-Gaussian uncertainties.
For the tagged channel, the low-m\(H\) selection is expected to appear as a peak in the invariant mass distribution of light-quark jets. The dijet invariant mass distributions before accounting the average jet energy scale difference between heavy- and light-quark jets. The dijet invariant mass distributions for the low- and high-m\(H\) selections are shown in Fig. 1.

These event selections define the “low-m\(H\)” selections. For larger Higgs boson masses, the Z bosons from H → ZZ decays have large momenta in the laboratory reference frame, resulting in smaller opening angles between their decay products. Therefore, “high-m\(H\)” selections are defined by the following additional requirements: (1) the two jets must have \(p_T > 45\) GeV, and (2) \(\Delta\phi_{jj} < \pi/2\) and \(\Delta\phi_{\ell\ell} < \pi/2\). These selections are applied when searching for a Higgs boson with m\(H\) ≥ 300 GeV, for which they improve the sensitivity.

Following this event selection, an \(H \rightarrow ZZ \rightarrow 4\ell q\bar{q}\) signal is expected to appear as a peak in the invariant mass distribution of the \(\ell\ell jj\) system, with \(m_\ell\ell jj\) around m\(H\). To improve the Higgs boson mass resolution, the energies of the jets forming each dijet pair are scaled by a single multiplicative factor to set the dijet invariant mass. The total efficiency for the selection of signal events is about 13% for m\(H\) = 200 GeV and 18% for m\(H\) = 600 GeV.

6. Background estimates

The principal background to this analysis is Z boson production in association with jets (Z + jets). The shape of this background is derived from \textsc{alpgen} Monte Carlo simulations and checked against data, while the normalisation is derived directly from data. Fig. 2(a) and (b) show the m\(\ell\ell jj\) distribution after the jet and E\(_{miss}\) requirements for events with the dijet invariant mass in sidebands of the Z boson mass: 40 GeV < m\(\ell\ell jj\) < 70 GeV or 105 GeV < m\(\ell\ell jj\) < 150 GeV. The Monte Carlo gives a good description of the shape, but predicts about 10% more events than are seen in the data. The numbers of events in the sidebands, after subtraction of the small contribution from other background sources, are used to derive scale factors to correct the normalisation of the Z + jets Monte Carlo to that observed in the data. For the untagged channel, scale factors are derived separately for the low- and high-m\(H\) selections; for the tagged channel, the low-m\(H\) selection is used to derive a single scale factor, as the tagged high-m\(H\) selection has very few events in the sidebands. Furthermore, as the shapes derived from the tagged \textsc{alpgen} MC samples suffer from significant statistical fluctuations, the shapes derived for the untagged selection are used for the tagged backgrounds, with appropriate scale factors applied. The shapes are found to agree within statistical uncertainties between the tagged and untagged MC samples.

Another significant background to this analysis is top quark production. As for Z + jets, the shape is taken from Monte Carlo and the normalisation is checked against data, using the sideband 60 GeV < m\(\ell\ell\) < 76 GeV or 106 GeV < m\(\ell\ell\) < 150 GeV of the dilepton mass distribution. Fig. 2(c) and (d) show the m\(jj\) distributions for these sidebands, both for the untagged selection (with the E\(_{miss}\) selection reversed) and the tagged selection. The normalisation of the \(t\bar{t}\) component of top quark production is calculated at NNLO using \textsc{hathor}[48]; for the single-top component, the MC@NLO normalisation is used. As the Monte Carlo agrees with the data within uncertainties, no scale factor is applied to the simulation in this case.

The small irreducible background from ZZ production is difficult to constrain from data due to the large Z + jets background component and possible contamination from the signal. Thus, this background is estimated entirely from Monte Carlo simulation. The small backgrounds from WZ and W + jets production are also taken from Monte Carlo simulation.

The background from multijet events in which jets are misidentified as isolated leptons is estimated from data. For the electron channel, a sample of events is selected that contains electron candidates that fail the selection requirements but pass loosened requirements; the normalisation is determined by a multicomponent fit to the m\(\ell\ell\) distribution in events containing at least two jets. The multijet background in the muon channel is estimated by dividing the dimuon + jets events into four categories based on whether the muons are isolated or non-isolated and on whether or not the invariant mass of the muon pair lies near the Z boson mass peak. The number of background events with two isolated muons with invariant mass consistent with Z boson decay can then be determined from the numbers of events observed in the other three categories (which contain negligible contamination from the signal) under the assumption that the two variables (isolation criteria and invariant mass) are uncorrelated. The muon channel multijet background is found to be negligible.

7. Systematic uncertainties

The theoretical uncertainties on the Higgs boson production cross section compiled in Ref.[10] are 15–20% for the gluon fusion process and 3–9% for the vector-boson fusion process, depending
on the Higgs boson mass.\textsuperscript{2} Signal samples generated with \textsc{pythia} instead of \textsc{powheg} are also used to evaluate the uncertainty on the selection efficiency due to the modelling of the signal kinematics. This results in a 3% (6%) uncertainty for the low- (high-)$m_H$ selection.

The uncertainty in the normalisation of the $Z$ + jets background from the procedure described in Section 6 is evaluated by comparing the scale factors obtained from the upper or lower sideband separately. It is taken as the difference between the scale factors or the statistical uncertainty, whichever is larger. It is found to be 1.4% for the low-$m_H$ untagged selection, 8.1% for the high-$m_H$ untagged selection, and 18% for the tagged selections. The uncertainty on the shapes of the $Z$ + jets (and $ZZ$) backgrounds is estimated using an alternate Monte Carlo sample generated with \textsc{pythia} instead of \textsc{alpgen} (or \textsc{mc@nlo}). The uncertainty on the $t\bar{t}$ cross section is found by adding the contributions from variations of the QCD renormalisation and factorisation scales and from the \textsc{cteq6.6} [34] parton distribution function (PDF) error set; the result is 9%. The diboson backgrounds, which are estimated directly from Monte Carlo, have a combined 5% scale and \textsc{cteq6.6} PDF uncertainty on the cross section; adding an additional 10% uncertainty, corresponding to the maximum difference seen between \textsc{mc@nlo} and k-factor scaled \textsc{pythia} results, yields an overall uncertainty of 11%. A 100% systematic uncertainty is assigned to the normalisation of the multijet background in the electron channel from the procedure described in Section 6 by comparing the result of fitting the $m_\ell\ell$ distribution before and after the requirement of at least two jets. The normalisation uncertainty for the small $W$ + jets background is taken to be 50%.

An overall 3.7% uncertainty from the total integrated luminosity\textsuperscript{50} is added to the uncertainties on all Monte Carlo processes (excluding $Z$ + jets, which is normalised to data), correlated across all samples.

There are also systematic uncertainty contributions from detector effects, including the lepton and jet trigger and identification efficiencies, the energy or momentum calibration and resolution of the leptons and jets, and the $b$-tagging efficiency and mistag rates. The dominant uncertainty on the tagged sample comes from the $b$-tagging efficiency, which corresponds to an average of 16% (23%) for the signal for the low- (high-) $m_H$ selection. For the untagged sample, the uncertainty on the jet energy scale is a major contribution, giving rise to an average uncertainty of 5% on the signal.

\section{Results}

Table 1 shows the numbers of candidates observed in data for each of the four selections compared with the background expectations. Fig. 3 shows the $m_{\ell\ell}$ distributions for both the tagged and untagged channels for the low- and high-$m_H$ selections.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
Selection & Low-$m_H$ & High-$m_H$ &\hline
Data & \num{56} & \num{34} & \hline
\textsc{pythia} & \num{58} & \num{36} & \hline
\textsc{powheg} & \num{54} & \num{32} & \hline
\end{tabular}
\end{table}
Table 1
The expected numbers of signal and background candidates in the \( H \to ZZ \to \ell^+\ell^-q\bar{q} \) channel, along with the numbers of candidates observed in data, for an integrated luminosity of 1.04 fb\(^{-1}\). The first error indicates the statistical uncertainty, the second error the systematic uncertainty.

| Signal m\( H \) | Untagged | Tagged |
|-----------------|-----------|--------|
| m\( H \) = 200 GeV | 33 ± 1 ± 6 | 2.2 ± 0.2 ± 0.6 | 0.6 ± 0.1 ± 0.2 |
| m\( H \) = 300 GeV | 7.0 ± 0.3 ± 1.5 | 9.8 ± 0.3 ± 1.8 | 1.1 ± 0.1 ± 0.3 |
| m\( H \) = 400 GeV | 5.5 ± 0.1 ± 1.0 | 5.5 ± 0.1 ± 1.0 | 0.6 ± 0.0 ± 0.2 |
| m\( H \) = 500 GeV | 2.5 ± 0.1 ± 0.5 | 2.5 ± 0.1 ± 0.5 | 0.3 ± 0.0 ± 0.1 |
| m\( H \) = 600 GeV | 1.5 ± 0.1 ± 0.5 | 1.5 ± 0.1 ± 0.5 | 0.3 ± 0.0 ± 0.1 |

Fig. 3. The invariant mass of the \( \ell\ell jj \) system for both the untagged (a), (c) and tagged (b), (d) channels, for the low-\( m_H \) (top row) and high-\( m_H \) (bottom row) selections. Examples of the expected Higgs boson signal for m\( H \) = 200 and 400 GeV are also shown; in the untagged plots, the signal has been scaled up by a factor of 10 to make it more visible.

No significant excess of events above the expected background is observed. Upper limits are set on the SM Higgs boson cross section at 95% CL as a function of mass, using the CL\(_S\) modified frequentist formalism with the profile likelihood test statistic\([51, 52]\). This is based on a likelihood that compares, bin-by-bin using Poisson statistics, the observed \( n_{\ell\ell jj} \) distribution to either the expected background or the sum of the expected background and a mass-dependent hypothesised signal. Systematic uncertainties, with their correlations, are incorporated as nuisance parameters, and the tagged and untagged channels are combined by forming the product of their likelihoods. Fig. 4 shows the resulting upper limit on the cross section for Higgs boson production and decay in the channel \( H \to ZZ \to \ell^+\ell^-q\bar{q} \) relative to the prediction of the Standard Model as a function of the hypothetical Higgs boson mass.

9. Summary

A search for the SM Higgs boson in the decay mode \( H \to ZZ \to \ell^+\ell^-q\bar{q} \) has been performed in the Higgs mass range 200
to 600 GeV using 1.04 fb$^{-1}$ of $\sqrt{s} = 7$ TeV pp data recorded by the ATLAS experiment at the LHC. No significant excess over the expected background is found. With the present integrated luminosity, there is insufficient sensitivity to exclude a SM Higgs boson in this channel at 95% CL. The ratio of the Higgs boson production cross section upper limits reported here to the SM Higgs boson production cross section ranges from 1.7 at $m_H = 360$ GeV to about 13 at $m_H = 600$ GeV. These limits are the most stringent to date in this channel.

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