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Search for the Standard Model Higgs boson in the decay channel $H \to ZZ(\ast) \to 4\ell$ with the ATLAS detector

ATLAS Collaboration

1. Introduction

The search for the Standard Model (SM) Higgs boson [1–3] is a major goal of the Large Hadron Collider (LHC) programme. Direct searches at the CERN LEP $e^+e^-$ collider led to a lower limit on the Higgs boson mass, $m_H$, of 114.4 GeV at 95% confidence level (CL) [4]. The searches at the Fermilab Tevatron $p\bar{p}$ collider have excluded at 95% CL the region 156 GeV $< m_H < 177$ GeV [5]. Results from the 2010 LHC run extended the search in the region 200 GeV $< m_H < 600$ GeV by excluding a Higgs boson with cross section larger than 5–20 times the SM prediction [6,7].

This Letter presents a search for the SM Higgs boson in the mass range from 110 to 600 GeV in the channel $H \to ZZ(\ast) \to \ell^+\ell^-\ell'^+\ell'^-$, where $\ell,\ell' = e,\mu$. Three distinct final states, $\mu\mu\mu\mu$ (4$\mu$), $e\mu\mu\mu$ (2$e2\mu$), and $e\mu\mu\mu$ (4$e$), are selected. The largest background to this search comes from continuum $ZZ(\ast)$ production. For $m_H < 180$ GeV, contributions from $Z + \text{jets}$ and $t\bar{t}$ processes, where the additional charged leptons arise either from semi-leptonic decays of heavy flavour or from light flavour jets misidentified as leptons, are important. The $pp$ collision data were recorded with the ATLAS detector at the LHC at $\sqrt{s} = 7$ TeV and correspond to an average integrated luminosity of 2.1 $fb^{-1}$ [8].

2. The ATLAS detector

The ATLAS detector [9] is a multi-purpose particle physics apparatus with forward–backward symmetric cylindrical geometry. The inner tracking detector (ID) consists of a silicon pixel detector, a silicon microstrip detector, and a transition radiation tracker. The ID is surrounded by a thin superconducting solenoid providing a 2 T magnetic field. A high-granularity lead-liquid argon (LAr) sampling calorimeter measures the energy and the position of electromagnetic showers. An iron–scintillator tile calorimeter provides hadronic coverage in the central rapidity range. The end-cap and forward rapidity regions are instrumented with LAr calorimetry for both electromagnetic and hadronic measurements. The muon spectrometer (MS) surrounds the calorimeters and consists of three large superconducting toroids, each with eight coils, a system of precision tracking chambers, and detectors for triggering. A three-level trigger system selects events to be recorded for offline analysis.

3. Data and simulation samples

The accumulated data are subjected to quality requirements ensuring that the relevant detector components were operating.
The number of $pp$ interactions in the same bunch crossing (pileup) is included in the simulation. The MC samples are reweighted to reproduce the observed distribution in the data.

4. Physics object identification and event selection

The data considered in this analysis were selected using single-lepton triggers. For electrons the threshold on the transverse energy, $E_T$, was 20–22 GeV depending on the LHC instantaneous luminosity and for muons the threshold on $p_T$ was 18 GeV. Both triggers are more than 99.5% efficient for events passing the offline selection described below.

Electron candidates consist of clusters of energy deposited in the electromagnetic calorimeter associated to ID tracks. The electrons must satisfy the “medium” electron criteria [43], which require the shower profiles to be consistent with those expected for electromagnetic showers and a well reconstructed ID track pointing to the corresponding cluster. The electron transverse momentum is computed from the cluster energy and the track direction.

Muon candidates are reconstructed by matching ID tracks with either full or partial tracks in the MS [43]. For the former case, the two independent momentum measurements are combined, whereas for the latter case the momentum is measured using the ID information only, with the MS providing muon identification. To reject cosmic rays, tracks are required to be consistent with having originated from the primary vertex, defined as the reconstructed vertex with the highest $\sum p_T^2$ of associated tracks.

Leptons from Higgs boson decays are expected to be isolated and to originate from a common vertex. Track and calorimeter isolation as well as transverse impact parameter significance requirements are therefore applied to further reduce the $Z$+jets and $tt$ contributions. The sum of $p_T$ of tracks within $\Delta R < 0.2$ of the lepton divided by the lepton $p_T$ is required to be less than 0.15, while the sum $E_T$ of the calorimeter cells within $\Delta R < 0.2$ around the lepton divided by the lepton $p_T$ is required to be less than 0.3. In the case of electrons, the calorimeter cells corresponding to the electromagnetic shower are subtracted. The transverse impact parameter significance, defined as the transverse impact parameter of the lepton with respect to the primary vertex divided by its uncertainty, for the two lowest $p_T$ leptons of the quadruplet in events with $m_{4\ell} < 190$ GeV is required to be less than 3.5 and 6 for muons and electrons respectively. The selection efficiency of the isolation and impact parameter requirements has been studied using data both for isolated leptons, with $Z \rightarrow \ell\ell$ decays and non-isolated leptons from semi-leptonic $b$- and $c$-quark decays in a heavy-flavour enriched dijet sample. Good agreement is observed between data and simulation.

Higgs boson candidates are searched by selecting two-flavour, opposite-sign isolated lepton pairs in an event. Each lepton must satisfy $p_T > 7$ GeV and be measured in the pseudorapidity range $|\eta| < 2.47$ for electrons and $|\eta| < 2.5$ for muons. The electron $p_T$ threshold is increased to 15 GeV in the transition region between the barrel and end-cap calorimeters ($1.37 < |\eta| < 1.52$). At least two leptons must have $p_T > 20$ GeV. The leptons are required to be well separated from each other with $\Delta R > 0.1$. The invariant mass of the lepton pair closest to the nominal Z boson mass ($m_Z$) is denoted by $m_{12}$ and it is required that $|m_{12} - m_Z| < 15$ GeV. The invariant mass of the remaining lepton pair, $m_{34}$, is required to be lower than 115 GeV and greater than a threshold depending on the reconstructed four lepton mass, $m_{4\ell}$, as summarized in Table 2. The final discriminative variable is $m_{4\ell}$, where the Higgs boson production would appear as a clustering of events. The width of the reconstructed Higgs boson mass distribution is dominated by experimental resolution at low $m_{4\ell}$ values.
with a full-width at half-maximum (FWHM) which varies according to decay mode and is between 4.5 (4μ) and 6.5 (4e) GeV for \( m_H = 130 \) GeV. At high \( m_H \) the reconstructed width is dominated by the natural width of the Higgs boson with a FWHM of approximately 35 GeV at \( m_H = 400 \) GeV.

### 5. Background estimation

The dominant \( ZZ^{(*)} \) background is estimated using MC simulation. Generated events are required to pass the complete analysis selection and the final yield is normalized to the integrated luminosity.

The \( t\bar{t} \) background is also estimated using MC simulation. Comparison of data to MC predictions, in a control sample of events with opposite sign electron–muon pairs consistent with the \( Z \) boson mass and with one or two additional charged leptons, are used to verify that the \( t\bar{t} \) background is small with respect to the dominant \( ZZ^{(*)} \) process and in agreement with expectation.

The \( Z + \) jets background is normalized using data. The control sample is formed by selecting events with a pair of same-flavour, opposite-sign isolated leptons consistent with the \( Z \) boson mass, \(|m_Z - m_{\ell\ell}| < 15 \) GeV, and a second same-flavour, opposite-sign lepton pair where only kinematic, no isolation or impact parameter, requirements are applied. At this stage, the dominant background source depends on the flavour of the second lepton pair: \( Z + \) light flavour jets dominates the final states with a second electron pair, while \( Zb\bar{b} \) production dominates the final states with a second muon pair after the contributions from \( t\bar{t}, ZZ^{(*)} \), and muons from in-flight \( \pi \) and \( K \) decays which correspond to 44% of the event yield are subtracted. The observed background, which is found to be in good agreement with expectation, is extrapolated to the signal region by means of the MC simulation.

### 6. Systematic uncertainties

Uncertainties on lepton reconstruction and identification efficiency, and on the momentum resolution and momentum scale are determined using samples of \( W, Z \) and \( J/\psi \) decays. The muon efficiency uncertainty results in an acceptance uncertainty on the signal and the irreducible background which is uniform over the mass range of interest and amounts to 1% (1.2%) for the 4μ (2e2μ) channel. The uncertainty on the electron efficiency results in an acceptance uncertainty of 3% (2%) for the 4e (2e2μ) channel at \( m_{4\ell} = 600 \) GeV reaching 15% (6%) at \( m_{4\ell} = 110 \) GeV.

A conservative theoretical uncertainty of 15% is assigned to the \( ZZ^{(*)} \) background contribution [44]. The \( Z + \) light flavour jets and \( Zb\bar{b} \) backgrounds are evaluated using data. A systematic uncertainty between 20% and 40% is assigned on their normalization to account for the statistical uncertainty in the control sample and the MC-based extrapolation to the signal region. The uncertainty on the \( t\bar{t} \) cross section is found to be 10% by adding linearly the contributions from variations of the renormalization and factorization scales to those of the parton distribution functions.

The theoretical uncertainties on the Higgs boson production cross section are 15–20% for the gluon fusion process and 3–9% for the vector-boson fusion process [17], depending on the Higgs boson mass.\(^2\) They include uncertainties on the QCD scale and on the parton distribution functions [46–49]. An additional 2% uncertainty is added to the signal selection efficiency due to the modelling of the signal kinematics. This is evaluated by comparing signal samples generated with PYTHIA and the default POWHEG samples.

The overall uncertainty on the total integrated luminosity is 3.7% [8].

### 7. Results

The number of events observed in each final state, separately for \( m_{4\ell} < 180 \) GeV and \( m_{4\ell} \geq 180 \) GeV, are compared with the ex-

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\(^2\) The limits presented in this study for \( m_H > 200 \) GeV assume cross sections based on on-shell Higgs boson production and decay and use MC generators with an ad hoc Breit–Wigner Higgs line shape. Recently potentially important effects related to off-shell Higgs boson production and interference effects between the Higgs boson signal and backgrounds have been discussed [17,45]. The inclusion of such effects may affect limits at high Higgs masses (\( m_H > 400 \) GeV).
Fig. 1. Invariant mass distributions (a) $m_{12}$, (b) $m_{34}$, and (c) $m_4\ell$ for the selected candidates. The data (dots) are compared to the background expectations from the dominant $ZZ^\ast$ process and the sum of $t\bar{t}$, $Zb\bar{b}$, and $Z$ + light flavour jets processes. Error bars represent 68.3% central confidence intervals.

Fig. 2. $m_4\ell$ distribution of the selected candidates, compared to the background expectation. Error bars represent 68.3% central confidence intervals. The signal expectation for three $m_H$ hypotheses is also shown.

Fig. 3. The expected (dashed) and observed (full line) 95% CL upper limits on the Higgs boson production cross section as a function of the Higgs boson mass, divided by the expected SM Higgs boson cross section. The green and yellow bands indicate the expected sensitivity with $\pm 1\sigma$ and $\pm 2\sigma$ fluctuations, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

Upper limits are set on the Higgs boson cross section at 95% CL, using the $C_L$ modified frequentist formalism [50] with the profile likelihood test statistic [51]. The test statistic is evaluated with a maximum likelihood fit of signal and background models to the observed $m_4\ell$ distribution. Fig. 3 shows the expected and observed 95% CL cross section upper limits as a function of $m_H$ and Table 4 summarizes the numerical values for selected $m_H$ points. The consistency with the background-only hypothesis is quantified using the $p$-value, the probability that a background-only experiment fluctuates more than the observation. The most significant deviation from the background-only hypothesis is observed for $m_H = 242$ GeV with a $p$-value of 4.9%. These results do not account for the so-called “look-elsewhere” effect [52]. The SM Higgs boson is excluded at 95% CL in the mass ranges 191–197, 199–200 and 214–224 GeV.

8. Summary

A search for the Standard Model Higgs boson in the decay channel $H \rightarrow ZZ^\ast \rightarrow 4\ell$ based on 2.1 fb$^{-1}$ of data recorded by the
ATLAS detector at $\sqrt{s} = 7$ TeV during the 2011 run, has been presented. No significant excess of candidates is observed in the mass range between 110 and 600 GeV with respect to the expected SM background. The observed (expected) 95% CL upper limit on the Higgs boson production cross section, in units of the SM cross section, is 0.99 (1.01) for $m_H = 194$ GeV, the region with the best expected sensitivity for this search. The SM Higgs boson is excluded at 95% CL in the mass ranges 191–197, 199–200 and 214–224 GeV.

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