PROCEEDINGS OF SCIENCE

Search for the Standard Model Higgs boson through the $\mathbf{H \to ZZ \to (ll\nu\nu, llqq)}$ decay channels with the ATLAS detector

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Searches for a heavy Standard Model (SM) Higgs boson decaying via $H \to ZZ \to \ell^+\ell^- q\bar{q}$ or $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$, where $\ell \equiv e, \mu$, are presented. The analyses are based on proton-proton collision data at $\sqrt{s} = 7$ TeV, collected by the ATLAS experiment at the CERN LHC during 2011 and corresponding to an integrated luminosity of 4.7 fb^{-1}. No significant excess of data above the expected SM background is observed in either channel. Upper limits on the production cross section for a Higgs boson with a mass in the range between 300 and 600 GeV are derived. The $H \to ZZ \to \ell^+\ell^- q\bar{q}$ decay channel excludes a SM Higgs boson in the mass ranges 300–322 GeV and 353–410 GeV, while the $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ channel excludes a wide mass range between 319–558 GeV, both at 95% CL.

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1. Introduction

In the Standard Model (SM), the Higgs Mechanism [1 – 3] is responsible for electroweak symmetry breaking and gives mass to the weak vector bosons and other particles. The search for the associated Higgs boson and the confirmation of this mechanism is one of the most important goals of the CERN Large Hadron Collider (LHC) physics programme.

Prior to the start of the 36$^{\text{th}}$ International Conference on High Energy Physics (ICHEP), the status of the experimental search for the Higgs boson was as follows. Direct searches at the CERN Large Electron-Positron Collider (LEP) excluded at 95% confidence level (CL) the production of a SM Higgs boson with mass m_H less than 114.4 GeV [4]. Searches at the Fermilab Tevatron $p\bar{p}$ collider excluded at 95% CL the regions 100–103 GeV and 147–180 GeV [5]. At the LHC, the combination of searches performed by the ATLAS experiment, using up to 4.9 fb^{-1} of $\sqrt{s} = 7$ TeV data, rule out the production of a SM Higgs boson at 95% in the regions 111.4–116.6 GeV, 119.4–122.2 GeV and 129.2–541 GeV [6]. The results presented here contributed significantly to the exclusion in the high m_H region. Corresponding combined results from CMS [7], using up to 4.8 fb^{-1} of $\sqrt{s} = 7$ TeV data, excluded at 95% CL the region 127.5–600 GeV. At the start of the conference, both ATLAS and CMS independently announced the 5σ observation of a new neutral boson with a mass of around 125 GeV, consistent with the SM Higgs boson; the results have subsequently been published in Refs [9, 10].

If m_H is larger than twice the Z boson mass, m_Z, the Higgs boson is expected to decay to a pair of on-shell Z bosons with a large branching ratio. A search for a SM Higgs boson in the mass range 200–600 GeV has been performed in the $H \to ZZ \to \ell^+\ell^- q\bar{q}$ and $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ ($\ell \equiv e, \mu$) decay channels [11, 12] using the ATLAS detector [8]. The data used in these searches were recorded during the 2011 LHC run with pp collisions at $\sqrt{s} = 7$ TeV and correspond to an integrated luminosity of 4.7 fb^{-1}. The signal processes include both gluon fusion and vector-boson fusion Higgs boson production mechanisms.

$H \to ZZ \to \ell^+\ell^- q\bar{q}$ and $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ events are characterised by two high transverse momentum leptons consistent with originating from a Z boson decay and either a pair of jets also consistent with a Z boson decay in the case of $H \to ZZ \to \ell^+\ell^- q\bar{q}$ or a large transverse momentum imbalance in the case of $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$. The selection of signal candidates and the estimation of the background processes in the two decay channels are outlined in the following sections.

2. H $\to$ ZZ $\to$ llqq decay channel

$H \to ZZ \to \ell^+\ell^- q\bar{q}$ candidate events are required to contain exactly two electrons or muons with transverse momentum $p_T > 20$ GeV in the pseudorapidity range $|\eta| < 2.5$. To ensure the leptons are isolated, the sum of the p_T of the tracks within a cone of radius $\Delta R = 0.2$ around the lepton must be less than 10% of the lepton's p_T. The invariant mass of the lepton pair must be consistent with the Z boson, $83 < m_{\ell\ell} < 90$ GeV, and the two muons in a pair must be oppositely charged (this is not required for electrons due to the higher charge misidentification rate). Events are then required to contain at least two jets with $p_T > 25$ GeV and $|\eta| < 2.5$. To suppress $t\bar{t}$ background, the magnitude of the missing transverse momentum must satisfy $E_{\mathrm{T}}^{\mathrm{miss}} < 50$ GeV.

To maximise the expected sensitivity of the analysis, events are split into two categories based on the identification of jets originating from b-quarks (b-jets): the "tagged" subchannel, containing

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events with exactly 2 b-jets, and the "untagged" channel, containing events with fewer than two b-jets. This exploits the fact that $\approx 21\%$ of signal events contain b-jets from $Z \to bb$ decays, while b-jets are produced less often in the main $(Z \to \ell\ell)$+jets background. Events are required to contain at least one dijet pair with invariant mass in the range $70 < m_{jj} < 105$ GeV. In the untagged channel, all pairs of jets formed from the three highest p_T jets are considered, leading to the possibility of multiple signal candidates per event; in the tagged channel only the b-jet pair is retained.

To exploit the fact that the boost of the Z bosons from the $H \to ZZ$ decay increases with m_H, the analysis is split into a "low-m_H" and "high-m_H" region, used to search for a Higgs boson with mass above and below 300 GeV, respectively. In the high-m_H case, additional cuts are placed on the jet p_T and the azimuthal opening angle between both the two leptons and the two jets.

The dominant background in this channel is Z+jets production. The shapes of the relevant kinematic distributions for this background are taken from MC, while the normalisation is derived from data. First, the relative fractions of the Z+light jets , $Z+c$ jets, and $Z+b$ jets components are estimated from data by fitting the distribution of the b-tagging discriminant with MC templates for each flavour. The overall $Z+$jets normalisation is then determined from data using a control region based on the m_{jj} sidebands. The number of events in the control region, after subtracting the MC contribution from other background sources, is used to derive scale factors to correct the Z+jets normalisation. The uncertainty on the shape of the Z+jets background is estimated by reweighting various kinematic distributions to cover any data to MC differences in the sidebands.

The second largest background, which is particularly important in the tagged channel, is top production. The shapes of the relevant kinematic distributions are taken from MC and the normalisation corrected to data using scale factors determined from a top control region defined by the $m_{\ell\ell}$ sidebands with the $E_{\mathrm{T}}^{\mathrm{miss}}$ selection reversed. The extraction of the scale factors is performed simultaneously for the $Z+$jets and top background, and in both cases separately for the untagged and tagged channels. The small irreducible background from ZZ and WZ production is taken directly from MC. The background due to multijet events is estimated from data and found to be negligible.

A $H \to ZZ \to \ell^+\ell^- q\bar{q}$ signal should 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 to set m_{jj} equal to the nominal m_Z. Figure 1 shows the resulting m_{lljj} distributions in the untagged and tagged channels for the high-m_H selection.

3. $\mathbf{H \to ZZ \to ll\nu\nu}$ decay channel

$H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ candidate events are required to contain an oppositely charged pair of isolated leptons, each having $p_T > 20$ GeV and $|\eta| < 2.5$, with an invariant mass consistent with the Z boson, $|m_{\ell\ell} - m_Z| < 15$ GeV. Events are rejected if they contain a third lepton with $p_T > 10$ GeV, which mainly reduces background due to WZ production. To suppress the background from top production, events are also rejected if they contain a b-jet with $p_T > 20$ GeV and $|\eta| < 2.5$. The event is then required to contain significant $E_{\mathrm{T}}^{\mathrm{miss}}$ arising from the $Z \to \nu\nu$ decay.

To exploit the increasing boost of the Z bosons with m_H, the search is again split into a low-m_H region and a high-m_H region, used to search for a Higgs boson with mass below or above 280 GeV, respectively. In the low-m_H region, events are required to satisfy $E_{\mathrm{T}}^{\mathrm{miss}} > 66$ GeV, while in the high-m_H region this is raised to $E_{\mathrm{T}}^{\mathrm{miss}} > 82$ GeV. These cuts significantly reduce the background from

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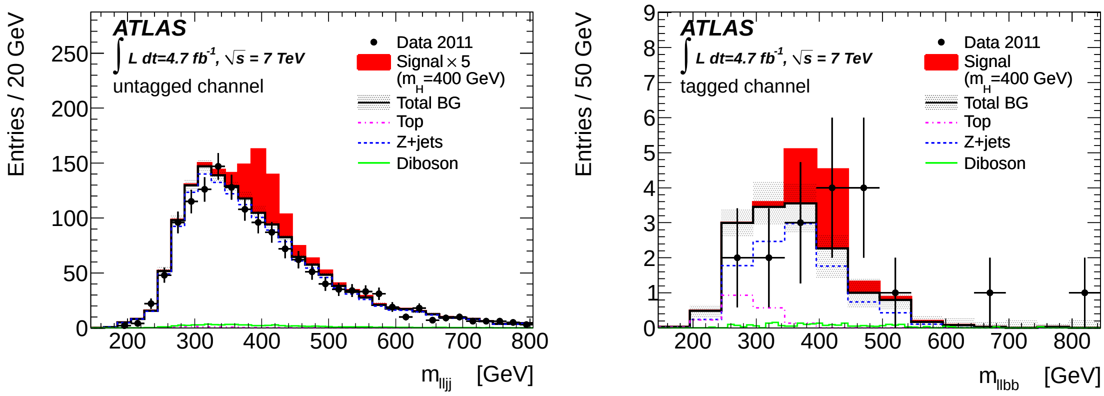

Figure 1: The invariant mass distributions of the $H \to ZZ \to \ell^+\ell^- q\bar{q}$ candidates for the high-m_H selection in the untagged (left) and the tagged (right) channels [11]. The expected Higgs boson signal for $m_H = 400$ GeV is shown, scaled up by a factor of 5 in the untagged case to make it more visible. The hashed band represents the combined systematic uncertainty on the total background prediction.

processes with no real $E_{\mathrm{T}}^{\mathrm{miss}}$ from undetected neutrinos. To reduce the background from events with fake $E_{\mathrm{T}}^{\mathrm{miss}}$ due to mis-measured jets, events are rejected if the azimuthal angle between the missing transverse momentum vector and the nearest jet, $\Delta\phi(\vec{p}_T{}^{\mathrm{miss}}, \vec{p}_T{}^{\mathrm{jet}})$, is small. To further exploit the mass-dependent kinematic features of $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ production, different cuts are placed on the azimuthal angle between the two leptons and between the missing transverse momentum vector and the $Z \to \ell\ell$ direction in the two m_H regions.

The $E_{\mathrm{T}}^{\mathrm{miss}}$ resolution is found to degrade in the later running periods due to an increased number of additional interactions per bunch crossing: "pile-up". This leads to an increase in the background from inclusive Z production and hence to retain sensitivity the analysis is split into a low and high pile-up data sample, corresponding to 2.3 fb^{-1} and 2.4 fb^{-1}, respectively.

SM diboson production forms a major background to this search, particularly in the high-m_H region. The irreducible ZZ component is taken from MC simulation, with a shape uncertainty obtained by comparing different MC generators, and normalised to the theoretical cross section. The WW and WZ components are similarly normalised; the WZ normalisation being verified in a control sample containing exactly three leptons.

The background from inclusive Z boson production, which gives a large contribution in the low-m_H channel, is taken from MC simulation and the normalisation verified in a control region formed from events failing the $\Delta\phi(\vec{p}_T{}^{\mathrm{miss}}, \vec{p}_T^{\mathrm{jet}})$ cut after the $E_{\mathrm{T}}^{\mathrm{miss}}$ requirement. The background from top production is again taken from MC and its normalisation verified in two independent control samples: the first consists of events containing oppositely-charged $e\mu$ pairs, while the second uses events in the m_{ll} sidebands containing a b-jet. The additional small background from inclusive W production is normalised from data using a sample of like-sign ee or $e\mu$ events in the m_{ll} sidebands. The multijet background, estimated from data, is found to be negligible.

A $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ signal is searched for as an excess of events in the transverse mass distribution of the $\ell\ell\nu\nu$ system. The transverse mass, m_T, is calculated assuming the lepton pair and $E_{\mathrm{T}}^{\mathrm{miss}}$ arise, respectively, from a $Z \to \ell\ell$ and $Z \to \nu\nu$ decay. Figure 2 shows the resulting m_T distributions in the low and high pile-up samples for the high-m_H selection.

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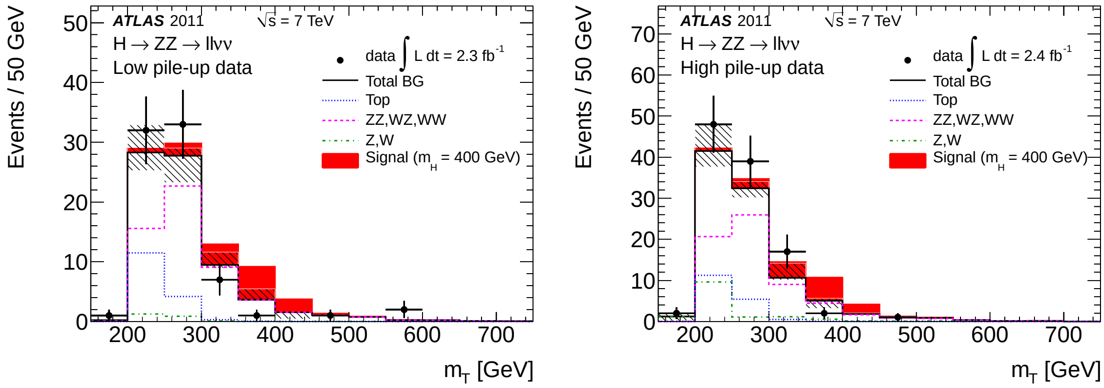

Figure 2: The transverse mass distributions of the $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ candidates for the high-m_H selection in the low (left) and high (right) pile-up data [12]. The expected Higgs boson signal for $m_H = 400$ GeV is shown. The hashed band represents the combined systematic uncertainty on the total background prediction.

4. Results

No significant excess of data above the expected SM background is observed in either the $H \to ZZ \to \ell^+\ell^- q\bar{q}$ or $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ decay channel. Upper limits are set on the Higgs boson production cross section relative to the SM prediction as a function of m_H. The limits are extracted based on a maximum likelihood fit to either the $m_{\ell\ell jj}$ or m_T distribution using the CL_s modified frequentist formalism [13] with the profile likelihood test statistic [14]. Individual channels or samples are combined by forming the product of their likelihoods. In the $H \to ZZ \to \ell^+\ell^- q\bar{q}$ search, the untagged and tagged channels contribute approximately equally across the m_H range. In the $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ search, the low pile-up sample dominates in the low-m_H region, while the low and high pile-up samples contribute approximately equally in the high-m_H region. Systematic uncertainties, along with their correlations, are incorporated as nuisance parameters.

The systematic uncertainity on the Higgs boson production cross section is taken from theory. In the absence of a full line shape calculation for the production mechanisms, taking into account the width of the Higgs boson and possible interference with the SM ZZ background, an additional m_H-dependent normalisation uncertainty is applied for $m_H > 300$ GeV. The uncertainty on the signal acceptance due to the production-process modelling is estimated by varying the parameters of the signal MC simulation, including initial and final state radiation, factorisation and normalisation scales and underlying event model. The normalisation uncertainty of the various background processes are estimated from the agreement of MC simulation with data in the control regions used to normalise them. The exception is the diboson production, where the uncertainty is taken from theory. When the normalisation is derived from theory, an additional luminosity uncertainty is applied. Various experimental uncertainties related to the selection and calibration of leptons and jets, the calculation of $E_{\mathrm{T}}^{\mathrm{miss}}$ and the identification of b-jets are also applied where appropriate.

Figure 3 shows the expected and observed limits in the $H \to ZZ \to \ell^+\ell^- q\bar{q}$ and $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ decay channels at 95% CL. The $H \to ZZ \to \ell^+\ell^- q\bar{q}$ channel excludes a SM Higgs boson in the mass ranges 300–322 GeV and 353–410 GeV at 95% CL, while the corresponding expected exclusion range is 351–404 GeV. The $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ channel excludes a wide mass range between 319–558 GeV at 95% CL, compared to an expected exclusion range of 319–558 GeV.

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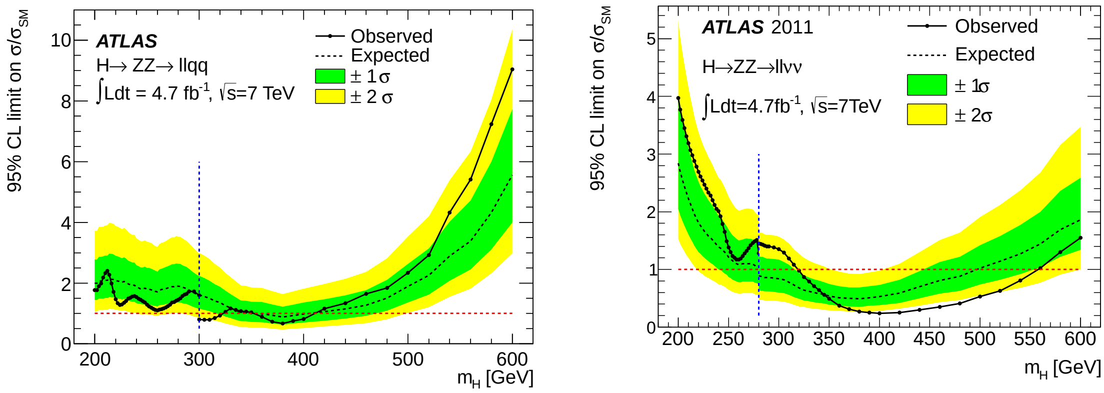

Figure 3: The expected (dashed line) and observed (solid line) 95% CL_s upper limits on the Higgs boson production cross section divided by the expected SM Higgs boson cross section for $H \to ZZ \to \ell^+\ell^- q\bar{q}$ (left) [11] and $H \to ZZ \to \ell^+\ell^- \nu\bar{\nu}$ (right) [12]. The inner and outer bands indicate the $\pm 1\sigma$ and $\pm 2\sigma$ ranges in which the limit is expected to lie in the absence of a signal. The horizontal dashed line shows the SM value of unity. The discontinuity in the limits at $m_H = 300$ GeV ($m_H = 280$ GeV) for the $H \to ZZ \to \ell^+\ell^- q\bar{q}$ ($H \to ZZ \to \ell^+\ell^- \nu\bar{\nu}$) channel is due to the transition between the use of the low- and high-m_H selections.

5. Summary

A search for a SM Higgs boson in the $H \to ZZ \to \ell^+\ell^- q\bar{q}$ and $H \to ZZ \to \ell^+\ell^- \nu\bar{\nu}$ decay channels has been performed over the Higgs mass range 200 to 600 GeV. The results are based on 4.7 fb^{-1} of $\sqrt{s} = 7$ TeV pp data recorded by the ATLAS experiment at the LHC in 2011. No evidence for a signal is observed and cross section limits are extracted, excluding the production of a SM Higgs boson over a wide range of masses above 300 GeV. The full details of the results presented here can be found in Refs. [11, 12].

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