An update to the combined search for the Standard Model Higgs boson with the ATLAS detector at the LHC using up to 4.9 fb$^{-1}$ of $pp$ collision data at $\sqrt{s} = 7$ TeV

The ATLAS Collaboration

Abstract

A preliminary combination of Standard Model Higgs boson searches with the ATLAS experiment, in a dataset corresponding to an integrated luminosity of 4.6 to 4.9 fb$^{-1}$ of $pp$ collision data collected at $\sqrt{s} = 7$ TeV at the LHC, is presented. A Standard Model Higgs boson is excluded at the 95% confidence level (CL) in the mass ranges from 110.0 GeV to 117.5 GeV, 118.5 GeV to 122.5 GeV, and 129 GeV to 539 GeV, while the range 120 GeV to 555 GeV is expected to be excluded in the absence of a signal. The mass regions between 130 GeV and 486 GeV are excluded at the 99% CL. An excess of events is observed around $m_H \sim 126$ GeV with a local significance of 2.5$\sigma$, where the expected significance in the presence of a Standard Model Higgs boson for that mass hypothesis is 2.9$\sigma$. The global probability for such an excess to occur in the full search mass range 110-600 GeV is approximately 30%, decreasing to 10% when restricted to the range 110-146 GeV.
1 Introduction

In 2011 the LHC delivered to ATLAS an integrated luminosity of 5.6 fb$^{-1}$ of $pp$ collisions at a centre-of-mass energy of 7 TeV. This outstanding performance allowed the ATLAS experiment to collect and analyse 4.6 fb$^{-1}$ to 4.9 fb$^{-1}$ of data to update its searches for the Standard Model (SM) Higgs boson [1–6]. The results of a combined search based on the $H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^- \ell^+\ell^-$ and $H \rightarrow \gamma\gamma$ channels using the full 2011 dataset [7, 8], the $H \rightarrow WW^{(*)} \rightarrow \ell^+\nu\ell^-\bar{\nu}$, $H \rightarrow ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ and $H \rightarrow ZZ \rightarrow \ell^+\ell^-q\bar{q}$ channels using 2.1 fb$^{-1}$ [9–13], and the $H \rightarrow WW \rightarrow \ell\nu q\bar{q}$ channel using 1.04 fb$^{-1}$ [14] were reported in Ref. [15].

This note describes the preliminary combined results obtained from updates to the $H \rightarrow WW^{(*)} \rightarrow \ell^+\ell^-\nu\bar{\nu}$, $H \rightarrow WW \rightarrow \ell\nu q\bar{q}$, $H \rightarrow ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$, and $H \rightarrow ZZ \rightarrow \ell^+\ell^-q\bar{q}$ analyses as well as the addition of the $H \rightarrow \tau^+\tau^-$ and the $ZH \rightarrow \ell^+\ell^- b\bar{b}$, $WH \rightarrow \ell\nu b\bar{b}$, $ZH \rightarrow \nu\nu b\bar{b}$ channels using the full 2011 dataset. The search analyses cover the mass range 110–600 GeV.

Direct searches of the SM Higgs boson have been carried out at other accelerators. Their latest most stringent constraints on the mass of the SM Higgs boson are a lower limit of 114.4 GeV at the 95% CL, set using the combined results of the four LEP experiments [16] and an excluded band of 156 GeV to 177 GeV from the combined Tevatron experiments [17].

2 Search Channels

In order to enhance sensitivity, most of the analysis channels are further broken into sub-channels with different signal and background contributions and different sensitivity to various systematic uncertainties. For $m_H < 200$ GeV the combined likelihood is derived from 68 disjoint signal and control regions. Table 1 provides a summary of the individual channels contributing to this combination. With respect to the previous combined search [15], the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^-\ell^+\ell^-$ analyses are unchanged, while the $H \rightarrow WW^{(*)} \rightarrow \ell^+\nu\ell^-\bar{\nu}$, $H \rightarrow WW \rightarrow \ell\nu q\bar{q}$, $H \rightarrow ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ and $H \rightarrow ZZ \rightarrow \ell^+\ell^-q\bar{q}$ are updated, and the $H \rightarrow b\bar{b}$ and $H \rightarrow \tau^+\tau^-$ channels are included.

- $H \rightarrow \gamma\gamma$: This analysis is unchanged with respect Ref. [15]. The $H \rightarrow \gamma\gamma$ search is carried out for $m_H$ hypotheses between 110 GeV and 150 GeV and uses an integrated luminosity of 4.9 fb$^{-1}$ [7]. The analysis in this channel separates events into nine independent categories of varying sensitivity. The categorisation is based on the pseudo-rapidity of each photon, whether it was reconstructed as a converted or unconverted photon, and on the momentum component of the diphoton system transverse to the thrust axis ($p_T\gamma\gamma$). The diphoton invariant mass distribution is fitted to estimate the background and used as a discriminating variable to distinguish signal and background. The mass resolution is approximately 1.7% for $m_H \sim 120$ GeV.

- $H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^-\ell^+\ell^-\ell^+\ell^-\ell^+\ell^-$: This analysis is unchanged with respect to the previous combined search [15]. The search is performed for $m_H$ hypotheses in the full 110 GeV to 600 GeV mass range using data corresponding to an integrated luminosity of 4.8 fb$^{-1}$ [8]. The main irreducible $ZZ^{(*)}$ background is estimated using Monte Carlo simulation. The reducible $Z$+jets background, which has an impact mostly for low four-lepton invariant masses, is estimated from control regions in the data. The top-quark ($t\bar{t}$) background normalisation is validated using a dedicated control sample. The events are categorised according to the lepton flavour combinations. The mass resolutions are approximately 1.5% in the four-muon channel and 2% in the four-electron channel for $m_H \sim 120$ GeV. The four-lepton invariant mass is used as a discriminating variable.

\footnote{A lepton $\ell$ denotes an electron or a muon.}
Table 1: Summary of the individual channels contributing to the combination. The central number in the three-part mass ranges indicates the transition from low-$m_H$ to high-$m_H$ optimised event selections.

<table>
<thead>
<tr>
<th>Higgs Decay</th>
<th>Subsequent Decays</th>
<th>Additional Sub-Channels</th>
<th>$m_H$ Range</th>
<th>L [fb$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma \gamma$</td>
<td>$\gamma \gamma$</td>
<td>9 sub-channels ($p_T$, $\eta_T$ conversion)</td>
<td>110-150</td>
<td>4.9</td>
</tr>
<tr>
<td>$H \rightarrow ZZ$</td>
<td>$e\ell\ell\ell$</td>
<td>${4e, 2e2\mu, 2\mu2e, 4\mu}$</td>
<td>110-600</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>$\ell\ell\nu\nu$</td>
<td>${ee, \mu\mu} \otimes {\text{low pile-up, high pile-up}}$</td>
<td>200-280-600</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>$\ell\ellqq$</td>
<td>${b$-tagged, untagged}</td>
<td>200-300-600</td>
<td>4.7</td>
</tr>
<tr>
<td>$H \rightarrow WW$</td>
<td>$\ell\nu\ell\nu$</td>
<td>${ee, e\mu, \mu\mu} \otimes {0$-jet, 1-jet, VBF}</td>
<td>110-300-600</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>$\ell\nuqq$</td>
<td>${e, \mu} \otimes {0$-jet, 1-jet}</td>
<td>300-600</td>
<td>4.7</td>
</tr>
<tr>
<td>$H \rightarrow \tau^+\tau^-$</td>
<td>$\ell\ell\ell\ell$</td>
<td>${e\mu} \otimes {0$-jet} $\oplus$ ${1$-jet, VBF, VH}</td>
<td>110-150</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>$\ell\tau_3\nu$</td>
<td>${e, \mu} \otimes {0$-jet} $\otimes$ ${E_T^{\text{miss}} \geq 20$ GeV} $\oplus$ ${e, \mu} \otimes {1$-jet, VBF}</td>
<td>110-150</td>
<td>4.7</td>
</tr>
<tr>
<td>$VH \rightarrow b\bar{b}$</td>
<td>$Z \rightarrow \nu\bar{\nu}$</td>
<td>$E_T^{\text{miss}} \in {120 - 160, 160 - 200, \geq 200$ GeV}</td>
<td>110-130</td>
<td>4.6</td>
</tr>
<tr>
<td></td>
<td>$W \rightarrow \ell\nu$</td>
<td>$p_T^{\ell} \in {&lt; 50, 50 - 100, 100 - 200, \geq 200$ GeV}</td>
<td>110-130</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>$Z \rightarrow \ell\ell$</td>
<td>$p_T^{\ell} \in {&lt; 50, 50 - 100, 100 - 200, \geq 200$ GeV}</td>
<td>110-130</td>
<td>4.7</td>
</tr>
</tbody>
</table>

• $H \rightarrow ZZ \rightarrow \ell^+\ell^-\nu\nu$ update: The analysis described in [11,15] was based on an integrated luminosity of 2.05 fb$^{-1}$ and was optimised for two search regions with $m_H$ hypotheses above and below 280 GeV and two lepton flavour categories. To achieve the best sensitivity, the present search, which uses an integrated luminosity of 4.7 fb$^{-1}$ [18], is additionally split between the first 2.3 fb$^{-1}$ of “low pile-up” collision data, where the average number of interactions per bunch crossing was about 6, and the latter 2.4 fb$^{-1}$ of “high pile-up” collisions, where the average number of interactions per bunch crossing was about 12. The selection is unaltered between the periods. The $\ell^+\ell^-$ pair invariant mass is required to be within 15 GeV of the Z-boson mass. The reverse requirement is applied to same-flavour leptons in the $H \rightarrow WW^{(*)} \rightarrow \ell^+\ell^-\nu\nu$ channel to avoid overlaps. The transverse mass of the dilepton and missing transverse energy system is used as a discriminating variable.

• $H \rightarrow ZZ \rightarrow \ell^+\ell^-q\bar{q}$ update: This analysis is updated with respect to the previous combined search [15]. The previous analysis used a dataset corresponding to an integrated luminosity of 2.05 fb$^{-1}$ [13], while the current analysis is based on an integrated luminosity of 4.7 fb$^{-1}$ [19]. It takes advantage of an improved $b$-tagging algorithm [20] and of the larger sample of data to better constrain systematic uncertainties on the background yield. The analysis is separated into search regions above and below $m_H=300$ GeV, where the event selections are independently optimised. The dominant background arises from Z+jets production, which is normalised from data using the sidebands of the dilepton invariant mass distribution. To profit from the sizable rate of Z’s decaying into a pair of $b$-quarks in the signal, the analysis is divided into two categories, the first containing events where the two jets are $b$-tagged and the second using events with less than two $b$-tags. Using the Z boson mass constraint improves the mass resolution of the $\ell\ell qq$ system by approximately 10%.

• $H \rightarrow WW^{(*)} \rightarrow \ell^+\ell^-\nu\nu$ update: Previous results using 2.05 fb$^{-1}$ are reported in Ref. [9]. The analysis has been updated using data corresponding to an integrated luminosity of 4.7 fb$^{-1}$ [21]. Furthermore, it now includes two new features. The first is that the previous event classification into a 0-jet and 1-jet categories is complemented with a 2-jet category. The latter selection targets the
fusion of vector bosons (VBF) production mode by requiring events to have two jets with a large difference in pseudo-rapidity ($|\Delta\eta_{jj}| > 3.8$), a large reconstructed invariant mass ($m_{jj} > 500$ GeV), and no additional jet with $p_T > 25$ GeV in the region $|\eta| < 3.2$. The second new feature is the use of the $WW$ transverse mass ($m_T$) distribution as a discriminating variable instead of a sliding cut.

- $H \rightarrow WW \rightarrow \ell\nu q\bar{q}'$: The contribution of this channel to the previous combined search was based on an integrated luminosity of 1.04 fb$^{-1}$ [14]. It is now updated using a dataset corresponding to an integrated luminosity of 4.7 fb$^{-1}$ [22]. The general strategy is unchanged, though the present analysis uses an updated modeling of the reconstructed $\ell\nu q\bar{q}'$ mass distribution, which is used as a discriminating variable. The reconstructed $\ell\nu q\bar{q}'$ mass is estimated using the $W$ boson mass constraint to reconstruct the mass of the $\ell\nu$ system. This channel is analysed separately according to lepton flavour and 0-jet and 1-jet categories, where the number of jets refers to jets additional to those selected as originating from the $W$-boson decay. Events with at least one $b$-tagged jet are rejected to reduce backgrounds from $t\bar{t}$ production.

- $H \rightarrow \tau\tau \rightarrow \ell^+\ell^- 4\nu$: In this channel events are separately analyzed in four independent categories associated to reconstructed jet activity [23]. Only $e^\pm\mu^\mp$ lepton combinations are considered in the 0-jet category. A large azimuthal angle between the lepton pair, $\Delta\phi_{\ell\ell} > 2.5$, is required. The other three categories consider all lepton flavour combinations together and require at least one jet with transverse energy in excess of 40 GeV. The boost of the Higgs boson also increases the efficiency against background processes such as $Z/\gamma^* \rightarrow \ell^+\ell^-$ and multijets. When the two leptons are of the same-flavour, the $Z \rightarrow \ell^+\ell^-$ background is further reduced by requiring the dilepton invariant mass to be smaller than the mass of the $Z$. The VBF category is selected by requiring two jets with a large difference in pseudo-rapidity ($|\Delta\eta_{jj}| > 3.0$), a large reconstructed invariant mass ($m_{jj} > 350$ GeV) and a veto on central jets. The $VH$ selection (where $V$ denotes a $W$ or a $Z$ boson) requires two jets with a small pseudo-rapidity difference ($|\Delta\eta_{jj}| < 2.0$) and an invariant mass compatible with that of a $W$ or $Z$ boson ($50$ GeV $< m_{jj} < 120$ GeV). Finally the 1-jet category excludes events passing the VBF and $VH$ selections. The main backgrounds are $Z \rightarrow \tau^+\tau^-$ and top-quark pair production. The reconstructed mass shape of the $Z$ boson production background is estimated using an embedding technique where muons from $Z$ decay events are substituted by simulated tau decays. All other backgrounds (including $Z$ decays to two electrons or muons, single top and diboson production) are taken from simulation, except the multijet background with jets faking leptons, which is estimated with a dedicated control sample. The reconstructed ditau mass is the effective mass, defined as the invariant mass formed by the $E_T^{miss}$ and the four-momenta of the two leptons, for events in the 0-jet category and the mass reconstructed in the collinear approximation for the other categories. The reconstructed ditau mass is used as a discriminating variable.

- $H \rightarrow \tau\tau \rightarrow \ell\tau_{had} 3\nu$: Events in this channel are triggered by inclusive single-lepton triggers [23]. The analysis requires one lepton (with transverse momentum in excess of 20 GeV for muons and 25 GeV for electrons) from a fully leptonic tau decay and an oppositely-charged hadronic tau candidate $\tau_{had}$, selected using a calorimeter jet associated to one or three tracks. Events with an additional lepton are removed to suppress the $Z/\gamma^* \rightarrow \ell^+\ell^-$, $t\bar{t}$ and $Wt$ (single top) backgrounds. The transverse mass of the lepton and missing energy system is required to be smaller than 30 GeV. The events in this channel are separately analyzed in three categories based on jet multiplicity. The 0-jet category requires that no jet with transverse energy in excess of 25 GeV be reconstructed. The category is then subdivided into four independent categories according to the flavour of the reconstructed lepton and whether the transverse missing energy ($E_T^{miss}$) is larger or smaller than 20 GeV. The 1-jet category requires at least one jet with transverse energy in excess of 25 GeV and
The sources of systematic uncertainties, and their effects on the signal and background yields and shapes of the kinematic distribution in each individual channel, are described in detail in Refs. [7, 8, 18, 19, 21–23, 26]. In the combination, systematic uncertainties are considered either as fully correlated or uncorrelated. Partial correlations are treated by separating a given source into a correlated and an uncorrelated component. The effect of each uncertainty is estimated independently for each channel. The dominant correlated systematic uncertainties are those on the theoretical predictions for the signal production cross

\[ E_T^{\text{miss}} > 20 \text{ GeV} \], and is divided into two sub-categories according to the flavour of the reconstructed lepton. Finally, the VBF category requires two reconstructed jets with oppositely-signed pseudorapidities, a difference in pseudorapidity of \( (|\Delta \eta_{jj}| > 3.0) \) and a large reconstructed invariant mass \( (m_{jj} > 300 \text{ GeV}) \). No central jet veto is applied in this analysis. A novel reconstruction procedure, using the Missing Mass Calculator (MMC) technique [25], is used to estimate the ditau invariant mass which does not assume a strict collinearity between the visible and invisible decay products of the tau leptons. The main background in this analysis is the \( Z/\gamma^* \rightarrow \tau^+ \tau^- \) process. As in the \( H \rightarrow \tau \tau \rightarrow \ell^+ \ell^- 4\nu \) case the invariant mass shape is estimated using an embedding technique. The results are derived using the reconstructed MMC mass as a discriminating variable.

- \( H \rightarrow \tau \tau \rightarrow \tau_{\text{had}} \tau_{\text{had}} 2\nu + \text{jet} \): Events are triggered using a selection of two hadronically-decaying taus with transverse energy thresholds varying according to the running conditions [23]. In the analysis, two oppositely-charged reconstructed hadronically-decaying taus are required along with a veto on the presence of reconstructed electrons or muons in the events. To reject the very large multijet background only events with one jet with transverse energy larger than 40 GeV, \( E_T^{\text{miss}} > 20 \text{ GeV} \) and a reconstructed invariant mass of the two taus and the jet greater than 225 GeV are kept. Further selection cuts on the fractions of undetected momentum in the collinear approximation are applied. The multijet background is estimated using data driven methods. The dominant remaining background is \( Z \rightarrow \tau^+ \tau^- \) production. As in the \( H \rightarrow \tau \tau \rightarrow \ell^+ \ell^- 4\nu \) and \( H \rightarrow \tau \tau \rightarrow \ell \tau_{\text{had}} 3\nu \) analyses, the embedding technique is used to estimate its shape. The \( \tau \tau \) invariant mass is estimated using the collinear approximation and is used as a discriminating variable.

- \( ZH \rightarrow \ell^+ \ell^- b\overline{b}, WH \rightarrow \ell \nu b \overline{b}, ZH \rightarrow \nu \nu b \overline{b} \): These three search channels were not included in Ref. [15]. The \( ZH \rightarrow \ell^+ \ell^- b\overline{b} \) and \( WH \rightarrow \ell \nu b \overline{b} \) analyses are based on an integrated luminosity of 4.7 fb\(^{-1}\), while the \( ZH \rightarrow \nu \nu b \overline{b} \) is based on 4.6 fb\(^{-1}\) [26]. All three analyses require exactly two b-tagged jets (one with \( p_T > 45 \text{ GeV} \) and the other with \( p_T > 25 \text{ GeV} \)) and the invariant mass of the two b-jets, \( m_{bb} \), is used as a discriminating variable. The \( ZH \rightarrow \ell^+ \ell^- b\overline{b} \) analysis requires a dilepton invariant mass in the range 83 GeV < \( m_{ll} < 99 \text{ GeV} \) and \( E_T^{\text{miss}} < 50 \text{ GeV} \) to suppress backgrounds from \( t\overline{t} \). The \( WH \rightarrow \ell \nu b \overline{b} \) analysis requires \( E_T^{\text{miss}} > 25 \text{ GeV} \), a transverse mass of the lepton-\( E_T^{\text{miss}} \) system of \( m_T > 40 \text{ GeV} \), and no additional leptons with \( p_T > 20 \text{ GeV} \). The \( ZH \rightarrow \nu \nu b \overline{b} \) analysis requires \( E_T^{\text{miss}} > 120 \text{ GeV} \), as well as \( p_T^{\nu \nu} > 30 \text{ GeV} \), where \( p_T^{\nu \nu} \) is the missing transverse momentum determined from the tracks associated to the primary vertex. To increase the sensitivity of the search, the \( m_{bb} \) distribution is examined in sub-channels with different signal-to-background ratios. In the searches with one or two charged leptons, the division is made according to four bins in transverse momentum \( p_T^{\nu \nu} \) of the reconstructed vector boson \( V \): \( p_T^{\nu \nu} < 50 \text{ GeV}, 50 \leq p_T^{\nu \nu} < 100 \text{ GeV}, 100 \leq p_T^{\nu \nu} < 200 \text{ GeV} \) and \( p_T^{\nu \nu} \geq 200 \text{ GeV} \). In the \( ZH \rightarrow \nu \nu b \overline{b} \) search the \( E_T^{\text{miss}} \) is used to define three sub-channels: \( 120 < E_T^{\text{miss}} < 160 \text{ GeV} \), \( 160 \leq E_T^{\text{miss}} < 200 \text{ GeV} \) and \( E_T^{\text{miss}} \geq 200 \text{ GeV} \). The individual channels are not broken into distinct lepton-flavour categories.

3 Systematic Uncertainties

The sources of systematic uncertainties, and their effects on the signal and background yields and shapes of the kinematic distribution in each individual channel, are described in detail in Refs. [7, 8, 18, 19, 21–23, 26]. In the combination, systematic uncertainties are considered either as fully correlated or uncorrelated. Partial correlations are treated by separating a given source into a correlated and an uncorrelated component. The effect of each uncertainty is estimated independently for each channel. The dominant correlated systematic uncertainties are those on the theoretical predictions for the signal production cross
sections and decay branching fractions, as well as those related to detector response aspects that impact the analyses through the reconstruction of electrons, photons, muon, jets, magnitude of the missing transverse momentum ($E_{\text{miss}}$) and $b$-tagging.

The uncertainty on the integrated luminosity is considered as fully correlated among channels and ranges from 3.7% to 3.9% depending on the data-taking period [27,28]. The uncertainty is larger for the last part of the 2011 data due to the increased pile-up.

The Higgs boson production cross sections are computed up to Next-to-next-to-leading order (NNNLO) [29–34] in QCD for the gluon fusion ($gg \rightarrow H$) process, including soft-gluon resummations up to next-to-next-to-leading order (NNLL) [35] and NLO electroweak (EW) corrections [36,37]. These results are compiled in Refs. [38–40]. The cross sections for the VBF process are estimated at NLO [41–43] and approximate NNLO QCD [44]. The associated $WH/ZH$ production processes ($q\bar{q} \rightarrow WH/ZH$) are computed at NLO [45,46], NNLO [47] and NLO EW [46]. The associated production with a $t\bar{t}$ pair ($q\bar{q}/gg \rightarrow t\bar{t}H$) is estimated at NLO [48–52]. The Higgs boson production cross sections and decay branching ratios [53–57], as well as their related uncertainties, are compiled in Ref. [58]. The QCD scale uncertainties for $m_H=120$ GeV amount to $^{+12}_{-8}$% for the $gg \rightarrow H$ process, $\pm 1\%$ for the $qq' \rightarrow qq'H$ and associated $WH/ZH$ processes, and $^{+3}_{-2}$% for the $q\bar{q}/gg \rightarrow t\bar{t}H$ process. The uncertainties related to the parton distribution functions (PDF) amount to $\pm 8\%$ for the predominantly gluon-initiated processes $gg \rightarrow H$ and $q\bar{q}/gg \rightarrow t\bar{t}H$, and $\pm 4\%$ for the predominantly quark-initiated $qq' \rightarrow q\bar{q}H$ and $WH/ZH$ processes [59]. The theoretical uncertainty associated with the exclusive Higgs boson production process with one additional jet in the $H \rightarrow WW^{(*)} \rightarrow \ell^+\ell^-\nu\bar{\nu}$ channel amounts to $\pm 20\%$ and is treated according to the prescription of Refs. [60,61]. Additional theoretical uncertainty on the signal normalisation, to account for effects related to off-shell Higgs boson production and interference with other SM processes, is assigned at high Higgs boson masses ($m_H \gtrsim 300$ GeV) as $150\% \times (m_H/\text{TeV})^3$ [61–64].

The detector-related sources of systematic uncertainty are modelled using the following classification: trigger and identification efficiencies, energy scale and energy resolution for electrons, photons and muons; jet energy scale (JES) and jet energy resolution, which include a specific treatment for $b$-jets; contributions to the $E_T^{\text{miss}}$ uncertainties uncorrelated with the JES; $b$-tagging and $b$-veto; and uncertainties associated with embedding the simulated detector response of $\tau$ decays in a $Z/\gamma' \rightarrow \mu^+\mu^-$ data sample. The effect of these systematic uncertainties depends on the topology of each final state, but is typically small compared to that from the theoretical prediction of the production cross section. The only exception is the jet energy scale uncertainty which can reach $\sim 20\%$ on the signal yield in channels such as $H \rightarrow WW \rightarrow \ell^\pm\nu\ell^\mp q\bar{q}$ and $H \rightarrow ZZ \rightarrow \ell^+\ell^-q\bar{q}$. The electron and muon energy scales are directly constrained by $Z \rightarrow e^+ e^-$ and $Z \rightarrow \mu^+ \mu^-$ events; the impact of the resulting systematic uncertainty on the four-lepton invariant mass is of the order of $\sim 0.5\%$ for electrons and negligible for muons. The impact of the photon energy scale systematic uncertainty on the diphoton invariant mass is approximately 0.6%.

4 Exclusion Limit Results

The signal strength, $\mu$, is defined as the ratio of a given Higgs boson production cross section ($\sigma$) to its SM value ($\sigma_{\text{SM}}$), $\mu = \sigma/\sigma_{\text{SM}}$. It is used to scale all channels coherently for a given $m_H$ hypothesis. The combination procedure used herein and described in Refs. [60,65,66] is based on the profile likelihood ratio test statistic $\lambda (\mu)$ [67], which extracts the information on the signal strength from the full likelihood including all the parameters describing the systematic uncertainties and their correlations. Exclusion limits are based on the $CL_s$ prescription [68]; a value of $\mu$ is regarded as excluded at the 95% (99%) CL when $CL_s$ takes on the corresponding value.

Figure 1 shows the expected and observed limits from the individual channels entering this combination (the expected limits from the individual channels without the observed limits overlaid are displayed in Fig. 9). The combined 95% CL exclusion limits on $\mu$ are shown in Fig. 2 as a function of $m_H$. These
Figure 1: The observed (solid) and expected (dashed) 95% CL cross section upper limits for the individual search channels, normalised to the SM Higgs boson production cross section, as a function of the Higgs boson mass. The expected limits are those for the background-only hypothesis i.e. in the absence of a Higgs signal.

results are based on the asymptotic approximation [67]. This procedure has been validated using ensemble tests and a Bayesian calculation of the exclusion limits with a uniform prior on the signal cross section. These approaches to the limit on \( \mu \) typically agree with the asymptotic median results to within a few percent.

The expected 95% CL exclusion region covers the \( m_H \) range from 120 GeV to 555 GeV. The observed 95% CL exclusion regions are from 110.0 GeV to 117.5 GeV, 118.5 GeV to 122.5 GeV, and 129 GeV to 539 GeV. The addition of the \( H \to \tau^+\tau^- \) and \( H \to b\bar{b} \) channels as well as the update to the \( H \to WW^{(*)} \to \ell^+\ell^-\nu\bar{\nu} \) channel bring a significant gain in sensitivity in the low-mass region with respect to the previous combined search [15]. The updates to the \( H \to WW^{(*)} \to \ell^+\ell^-\nu\bar{\nu}, H \to WW \to \ell\nu q\bar{q}', H \to ZZ \to \ell^+\ell^-\ell^+\ell^- \), and \( H \to ZZ \to \ell^+\ell^- q\bar{q} \) channels improve the sensitivity in the high-mass region. A small mass region near \( m_H \sim 245 \) GeV was not excluded at the 95% CL in the combined search of Ref. [15], mainly due to a slight excess in the \( H \to ZZ^{(*)} \to \ell^+\ell^-\ell^+\ell^- \) channel. This mass region is now excluded. Figure 3 shows the \( C_L \) value for \( \mu = 1 \), where it can be seen that the regions between 130 GeV and 486 GeV are excluded at the 99% CL. The observed exclusion covers a large part of the expected exclusion range, with the exception of the low mass region where an excess of events above the expected background is observed.
Figure 2: The observed (full line) and expected (dashed line) 95% CL combined upper limits on the SM Higgs boson production cross section divided by the Standard Model expectation as a function of $m_H$ in the full mass range considered in this analysis (a) and in the low mass range (b). The dotted curves show the median expected limit in the absence of a signal and the green and yellow bands indicate the corresponding 68% and 95% intervals.
Figure 3: The value of the combined $CL_s$ for $\mu = 1$ (testing the Standard Model Higgs boson hypothesis) as a function of $m_H$ in the full mass range of this analysis (a) and in the low mass range (b). The regions with $CL_s < \alpha$ are excluded at the $(1 - \alpha)$ CL or stronger. When the best-fit value of the strength parameter exceeds the tested signal hypothesis ($\mu = 1$) the observed $CL_s$ is bound to be equal to 50% by construction.
5 Compatibility with the background only hypothesis

An excess of events is observed near $m_H \sim 126$ GeV in the $H \to \gamma \gamma$ and $H \to ZZ^{(*)} \to \ell^+ \ell^- \ell^+ \ell^-$ channels, both of which provide fully reconstructed candidates with high-resolution in invariant mass. The $H \to WW^{(*)} \to \ell^+ \nu \ell^- \bar{\nu}$ channel also showed a broad excess of events (at the 1.4$\sigma$ level) with 2.05 fb$^{-1}$ in the transverse mass distribution. The analysis is updated with the full data sample recorded in 2011 (4.7 fb$^{-1}$) which also allowed a more precise understanding of the detector response, the backgrounds and their systematic uncertainties. Several analysis improvements have also been introduced (see Section 2). The updates to the low mass analyses improve the combined sensitivity by about 15% for Higgs boson masses of around 126 GeV with respect to the results presented in [15]. The data in this channel are now more consistent with the background-only expectation.

The significance of an excess is quantified by the probability ($p_0$) that a background-only experiment is more signal-like than that observed. The profile likelihood ratio test statistic is defined such that $p_0$ cannot exceed 50%. The local $p_0$ probability is assessed for a fixed $m_H$ hypothesis and the equivalent formulation in terms of number of standard deviations is referred to as the local significance. The probability for a background-only experiment to produce a local significance of this size or larger anywhere in a given mass region is referred to as the global $p_0$. The corresponding reduction in the significance is referred to as the look-elsewhere effect and is estimated using the prescription described in Refs. [60, 69].

The observed local $p_0$ values, calculated using the asymptotic approximation, as a function of $m_H$ and the expected value in the presence of a SM Higgs boson signal at that mass are shown in Fig. 4 and Fig. 5 in the entire search mass range and in the low mass range. The asymptotic approximation has been verified using ensemble tests which yielded numerically consistent results.

The largest local significance for the combination is observed for $m_H = 126$ GeV, where it reaches 2.6$\sigma$ with an expected value in the presence of a signal at that mass of 2.9$\sigma$. The observed (expected) local significances for $m_H = 126$ GeV are 2.8$\sigma$ (1.4$\sigma$) in the $H \to \gamma \gamma$ channel, 2.1$\sigma$ (1.4$\sigma$) in the $H \to ZZ^{(*)} \to \ell^+ \ell^- \ell^+ \ell^-$ channel and 0.2$\sigma$ (1.6$\sigma$) in the $H \to WW^{(*)} \to \ell^+ \nu \ell^- \bar{\nu}$ channel.

The significance of the excess is mildly sensitive to energy scale systematic (ESS) uncertainties and resolution for photons and electrons. The muon energy scale systematic uncertainties are smaller and therefore neglected. The presence of these uncertainties, which affect the shape and position of the signal distributions, lead to a small deviation from the asymptotic approximation. The observed $p_0$ including these effects is therefore estimated using ensemble tests. The results are displayed in Fig. 5 as a function of $m_H$. The observed effect of the ESS uncertainty is small and reduces the maximum local significance from 2.6$\sigma$ to 2.5$\sigma$.

To illustrate the effect of the updated analyses in the low mass range, Fig. 6(a) shows the local $p_0$ in various combinations, starting from the high resolution channels, $H \to \gamma \gamma$ and $H \to ZZ^{(*)} \to \ell^+ \ell^- \ell^+ \ell^-$, followed by the addition of the $H \to WW^{(*)} \to \ell^+ \ell^- \nu \bar{\nu}$ channel, and finally the $H \to b\bar{b}$ and $H \to \tau^+ \tau^-$ channels. The combination of the low mass resolution channels, $H \to WW^{(*)} \to \ell^+ \ell^- \nu \bar{\nu}, H \to b\bar{b}$ and $H \to \tau^+ \tau^-$, is also shown in terms of cross section upper limits in Fig. 6(b).

The global $p_0$ for local excesses depend on the range of $m_H$ and the channels considered. The global $p_0$ associated with a 2.8$\sigma$ excess anywhere in the $H \to \gamma \gamma$ search domain 110–150 GeV is approximately 7%. A 2.1$\sigma$ excess anywhere in the $H \to ZZ^{(*)} \to \ell^+ \ell^- \ell^+ \ell^-$ search range 110–600 GeV corresponds to a global $p_0$ of approximately 30%. The global probability for such an excess in the combined search to occur anywhere in the mass range 110–600 GeV is estimated to be approximately 30%, decreasing to 10% in the range 110–146 GeV, which is not excluded at the 99% confidence level by the LHC combined SM Higgs boson search [62].

The best-fit value of $\mu$, denoted $\hat{\mu}$, is displayed for the combination of all channels in Fig. 7 and in Fig. 8 for individual channels as a function of the $m_H$ hypothesis. The bands around $\hat{\mu}$ illustrate the $\mu$ interval corresponding to $-2\ln \lambda(\mu) < 1$ and represent an approximate $\pm 1\sigma$ variation. When evaluating
Figure 4: The local probability $p_0$ for a background-only experiment to be more signal-like than the observation in the full mass range of this analysis (a) and in the low mass range (b) as a function of $m_H$. The dashed curves show the median expected local $p_0$ under the hypothesis of a Standard Model Higgs boson production signal at that mass. The horizontal dashed lines indicate the $p$-values corresponding to significances of $1\sigma$ to $5\sigma$. 

ATLAS Preliminary 2011 Data

(a) $m_H$ vs $p_0$

(b) $m_H$ vs $p_0$ (low mass range)
exclusion limits and significance, $\mu$ is not allowed to be negative; however, this restriction is not applied in Fig. 7 and Fig. 8, in order to illustrate the presence and extent of downward fluctuations. Nevertheless, the $\mu$ parameter is still bounded to prevent negative values of the probability density functions in the individual channels, hence for negative $\hat{\mu}$ values close to the boundary, the $-2 \ln \lambda (\mu) < 1$ region does not reflect a 68% confidence interval. The excess observed for $m_H = 126$ GeV corresponds to $\hat{\mu}$ of approximately $0.9^{+0.4}_{-0.3}$, which is compatible with the signal strength expected from a SM Higgs boson at that mass ($\mu = 1$).

6 Conclusion

The full dataset recorded by the ATLAS experiment in 2011, corresponding to an integrated luminosity of 4.6 fb$^{-1}$ to 4.9 fb$^{-1}$, has been used to update searches for the SM Higgs boson. Higgs boson masses between 120 GeV and 555 GeV are expected to be excluded at the 95% CL or higher. The observed 95% CL exclusion regions extend from 110.0 GeV to 117.5 GeV, 118.5 GeV to 122.5 GeV, and 129 GeV to 539 GeV. The mass regions between 130 GeV and 486 GeV are excluded at the 99% CL.

An excess of events is observed in the $H \rightarrow \gamma \gamma$ and $H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^-\ell^+\ell^-$ channels at Higgs boson mass hypotheses close to 126 GeV, with local significances of $2.8\sigma$ and $2.1\sigma$ respectively. The expected sensitivities for a 126 GeV SM Higgs boson are $1.4\sigma$ for both channels. The local significance of the observed excess when all channels are combined is $2.5\sigma$, where the expected significance in the presence of a SM Higgs boson with $m_H=126$ GeV is $2.9\sigma$. A preliminary estimate of the global probability for such an excess to occur anywhere in the full explored Higgs boson mass region (from 110 GeV to
600 GeV) is approximately 30% and in the range not excluded at the 99% confidence level by the LHC combined Higgs boson search results [62] (from 110 GeV to 146 GeV) it amounts to approximately 10%.

References

10. ATLAS Collaboration, Search for a Standard Model Higgs boson in the $H \rightarrow ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ decay channel with the ATLAS detector, Phys. Rev. Lett. 107 (2011) 221802.
11. ATLAS Collaboration, Search for a Standard Model Higgs in the $H \rightarrow ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ decay channel with 2.05 fb$^{-1}$ of ATLAS data, ATLAS-CONF-2011-148 (2011).
13. ATLAS Collaboration, Search for a Standard Model Higgs Boson in the mass range 200-600 GeV in the channel $H \rightarrow ZZ \rightarrow \ell^+\ell^q\bar{q}$ using the ATLAS Detector, ATLAS-CONF-2011-150 (2011).
15. Combined search for the Standard Model Higgs boson using up to 4.9 fb$^{-1}$ of pp collision data at $\sqrt{s} = 7$ TeV with the ATLAS detector at the LHC, arXiv:1202.1408 [hep-ex].


[18] ATLAS Collaboration, *Search for a Standard Model Higgs boson in the $H \to ZZ \to \ell\ell
\nu\nu$ with 4.7 fb$^{-1}$*, ATLAS-CONF-2012-016 (2012).

[19] ATLAS Collaboration, *Search for a heavy Standard Model Higgs boson in the mass range 200-600 GeV in the channel $H \to ZZ \to \ell\ell qq$, ATLAS-CONF-2012-017 (2012).


[21] ATLAS Collaboration, *Search for a Standard Model Higgs boson in the $H \to WW^{(*)} \to \ell\nu\ell\nu$ decay mode with 4.7 fb$^{-1}$ of ATLAS data at $\sqrt{s} = 7$ TeV*, ATLAS-CONF-2012-012 (2012).


Figure 6: (a) The local probability $p_0$ for a background-only experiment to be more signal-like than the observation for various combinations of channels: the $H \rightarrow \gamma \gamma$ and $H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^+\ell^-\ell^-$ channels (blue), the $H \rightarrow \gamma \gamma, H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^-\ell^+\ell^-$ and $H \rightarrow WW^{(*)} \rightarrow \ell^+\nu\ell^-\nu$ channels (red), and the $H \rightarrow \gamma \gamma, H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^-\ell^+\ell^-, H \rightarrow WW^{(*)} \rightarrow \ell^+\nu\ell^-\nu, H \rightarrow b\bar{b}$ and $H \rightarrow \tau^+\tau^-$ channels (black). The dashed curves show the median expected value under the hypothesis of a SM Higgs boson signal at that mass. (b) The 95% CL upper limit on the Standard Model Higgs boson production cross section divided by the Standard Model expectation as a function of $m_H$ is indicated by the solid curves for the combination of the low mass resolution channels $H \rightarrow WW^{(*)} \rightarrow \ell^+\nu\ell^-\nu, H \rightarrow b\bar{b}$ and $H \rightarrow \tau^+\tau^-$ (red) and the combination of the high mass resolution $H \rightarrow \gamma \gamma$ and $H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^-\ell^+\ell^-$ channels (blue). The dashed curves show the median expected limit in the absence of a signal and the green and yellow bands indicate the corresponding 68% and 95% intervals for the full combination.
Figure 7: The best-fit signal strength $\mu = \sigma / \sigma_{SM}$ as a function of the Higgs boson mass hypothesis in the full mass range of this analysis (a) and in the low mass range (b). The $\mu$ value indicates by what factor the SM Higgs boson cross section would have to be scaled to best match the observed data. The band shows the interval around $\hat{\mu}$ corresponding to a variation of $-2 \ln \lambda(\mu) < 1$. 
Figure 8: The best-fit signal strength $\mu = \sigma / \sigma_{SM}$ as a function of the Higgs boson mass hypothesis for the $H \rightarrow \gamma \gamma$ (a), the $H \rightarrow \tau \tau$ (b), the $H \rightarrow ZZ(\ast) \rightarrow \ell^+\ell^-\ell^+\ell^-$ channel in the low mass region (c), the $H \rightarrow ZZ(\ast)$ across the full search range (d), the $H \rightarrow bb$ (e), and $H \rightarrow WW(\ast)$ (f) individual channels. The $\mu$ value indicates by what factor the SM Higgs boson cross section would have to be scaled to best match the observed data. The band shows the interval around $\hat{\mu}$ corresponding to a variation of $-2 \ln \lambda(\mu) < 1$. 

19
Figure 9: The expected 95% CL cross section upper limits for the individual search channels and their combination, normalised to the SM Higgs boson production cross section, as functions of the Higgs boson mass.