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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 ☆

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ABSTRACT

A combined search for the Standard Model Higgs boson with the ATLAS experiment at the LHC using datasets corresponding to integrated luminosities from 1.04 fb^{-1} to 4.9 fb^{-1} of pp collisions collected at $\sqrt{s} = 7$ TeV is presented. The Higgs boson mass ranges 112.9–115.5 GeV, 131–238 GeV and 251–466 GeV are excluded at the 95% confidence level (CL), while the range 124–519 GeV is expected to be excluded in the absence of a signal. An excess of events is observed around $m_H \sim 126$ GeV with a local significance of 3.5 standard deviations (σ). The local significances of $H \to \gamma\gamma$, $H \to ZZ^{(*)} \to \ell^+\ell^-\ell'^+\ell'^-$ and $H \to WW^{(*)} \to \ell^+\nu\ell'^-\bar{\nu}$, the three most sensitive channels in this mass range, are 2.8σ, 2.1σ and 1.4σ, respectively. The global probability for the background to produce such a fluctuation anywhere in the explored Higgs boson mass range 110–600 GeV is estimated to be $\sim$1.4% or, equivalently, 2.2σ.

1. Introduction

The discovery of the mechanism for electroweak symmetry breaking (EWSB) is a major goal of the physics programme at the Large Hadron Collider (LHC). In the Standard Model (SM), EWSB is achieved by invoking the Higgs mechanism, which requires the existence of the Higgs boson [1–6]. In the SM, the Higgs boson mass, m_H, is a priori unknown. However, for a given m_H hypothesis, the production cross sections and branching fractions of each decay mode are predicted, which enables a combined search with data from several decay channels.

Direct searches at the CERN LEP e^+e^- collider excluded the production of a SM Higgs boson with mass below 114.4 GeV at the 95% CL [7]. The combined searches at the Fermilab Tevatron $p\bar{p}$ collider have excluded the production of a Higgs boson with mass between 156 GeV and 177 GeV at the 95% CL [8].

In 2011, the LHC delivered to ATLAS an integrated luminosity of 5.6 fb^{-1} of pp collisions at 7 TeV centre-of-mass energy. The ATLAS experiment collected and analysed an integrated luminosity corresponding to up to 4.9 fb^{-1} of data fulfilling all the data quality requirements to search for the SM Higgs boson. In this Letter a combined search using six distinct channels, covering the mass range 110 GeV to 600 GeV, is presented. The Higgs boson is produced primarily through the gluon fusion process and the following decay modes are considered: $H \to \gamma\gamma$, $H \to ZZ^{(*)} \to \ell^+\ell^-\ell'^+\ell'^-$, $H \to ZZ \to \ell^+\ell^-q\bar{q}$, $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$, $H \to WW^{(*)} \to \ell^+\nu\ell'^-\bar{\nu}$, and $H \to WW \to \ell\nu q\bar{q}'$, where ℓ denotes an electron or a muon. New limits on SM Higgs boson production are established and the significance of an excess of events observed in the low mass region around $m_H = 126$ GeV is quantified.

2. Search channels

All search analyses are described in their respective references [9–14] and therefore only the main features relevant to the statistical combination of the various channels are summarised here. Two channels, the $H \to ZZ \to \ell^+\ell^-q\bar{q}$ and $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$, have been updated to a data sample corresponding to an integrated luminosity larger than that used in the previously published results and are described in more detail.

The $H \to \gamma\gamma$ search is carried out for m_H hypotheses between 110 GeV and 150 GeV and uses an integrated luminosity of 4.9 fb^{-1} [9]. The analysis in this channel separates events into nine independent categories of varying sensitivity. The categorisation is based on the direction of each photon and whether it was reconstructed as a converted or unconverted photon, together with the momentum component of the diphoton system transverse to the thrust axis. The diphoton invariant mass $m_{\gamma\gamma}$ is used as a discriminating variable to distinguish signal and background, to take advantage of the mass resolution of approximately 1.4% for $m_H \sim 120$ GeV. The distribution of $m_{\gamma\gamma}$ in the data is fit to a smooth function to estimate the background. The inclusive invariant mass distribution of the observed candidates, summing over all categories, is shown in Fig. 1(a).

The search in the $H \to ZZ^{(*)} \to \ell^+\ell^-\ell'^+\ell'^-$ channel 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} [10]. The main irreducible $ZZ^{(*)}$ background is estimated

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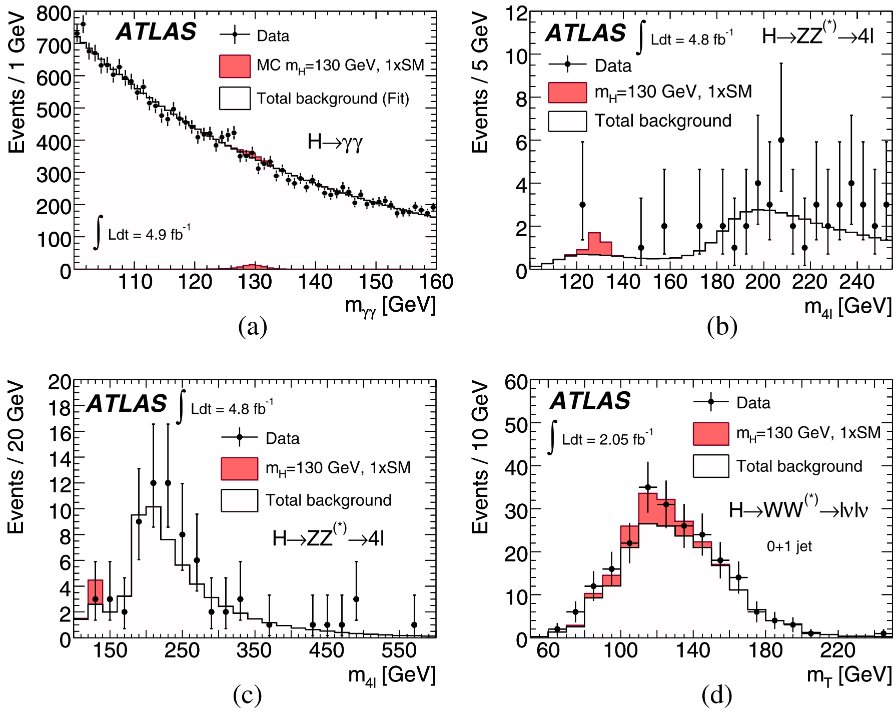

Fig. 1. Distributions of the reconstructed invariant or transverse mass for the selected candidate events and for the total background and signal ($m_H = 130$ GeV) expected in the $H \to \gamma\gamma$ (a), the $H \to ZZ^{(*)} \to \ell^+\ell^-\ell'^+\ell'^-$ in the low mass region (b) and the entire mass range (c), and the $H \to WW^{(*)} \to \ell^+\nu\ell'^-\bar{\nu}$ (d) channels.

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 background normalisation is validated in a control sample of events with an opposite sign electron–muon pair with an invariant mass consistent with that of the Z boson and two leptons of the same flavour. 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. Its distribution for events selected after all cuts is displayed in Fig. 1(b) for the low mass range and Fig. 1(c) for the full mass range.

The $H \to WW^{(*)} \to \ell^+\nu\ell'^-\bar{\nu}$ search is performed as an event counting analysis for m_H hypotheses between 110 GeV and 300 GeV, using an integrated luminosity of 2.05 fb^{-1} [11]. The main background contribution, from non-resonant WW production, is estimated from the data using control regions based on the dilepton invariant mass $m_{\ell\ell}$. The analysis is separated into 0-jet and 1-jet categories as well as according to lepton flavour. In the 1-jet category, a b-jet veto is applied to reject events from top-quark production. The relative fractions of the background contributions expected in the signal and control regions are taken from Monte Carlo simulation. The transverse mass distribution of events for both jet categories is displayed in Fig. 1(d).

The $H \to WW \to \ell\nu q\bar{q}'$ analysis covers m_H hypotheses in the 240 GeV to 600 GeV range and is carried out using data corresponding to an integrated luminosity of 1.04 fb^{-1} [12]. This channel is also separated according to lepton flavour and into 0-jet and 1-jet categories, where the number of jets refers to those in addition to the jets selected as originating from the W-boson decay. Events with at least one b-tagged jet are rejected to reduce backgrounds from top-quark production. The $\ell\nu q\bar{q}'$ mass is reconstructed using a constraint to the $\ell\nu$ system to W-boson mass. It is used as a discriminating variable and its distribution is illustrated in Fig. 2(a).

The search in the $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ channel is performed in the 200 GeV to 600 GeV range of m_H. The analysis described in Ref. [13] is based on data corresponding to an integrated luminosity of 1.04 fb^{-1}. It has been updated using a dataset corresponding to an integrated luminosity of 2.05 fb^{-1}. The main change in the event selection is the use of an improved b-tagging algorithm [15] to veto events with jets likely to have originated from b-quarks. The analysis is tuned for two search regions with m_H hypotheses above and below 280 GeV and separated into lepton flavour categories. 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 flavor leptons in the $H \to WW^{(*)} \to \ell^+\nu\ell'^-\bar{\nu}$ channel to avoid overlaps. The transverse mass is used as a discriminating variable. Its distribution is shown in Fig. 2(b) for the high m_H search. In total 175 events are selected in the low m_H search and 192 ± 23 are expected from the background. Similarly, the high-mass search selects 89 events, while 100 ± 11 are expected from the background. The expected number of signal events in the low mass search for $m_H = 200$ GeV is 9.9 ± 1.8 and 19.6 ± 3.4 for the high-mass selection for $m_H = 400$ GeV.

The analysis of the $H \to ZZ \to \ell^+\ell^-q\bar{q}$ channel, carried out in the m_H range from 200 GeV to 600 GeV using data corresponding to an integrated luminosity of 1.04 fb^{-1}, is described in Ref. [14]. It has been updated using a dataset corresponding to an integrated luminosity of 2.05 fb^{-1}, taking advantage of the improved b-tagging algorithm 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 branching fraction of the Z 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 with events with fewer than two b-tags. Using the Z-boson

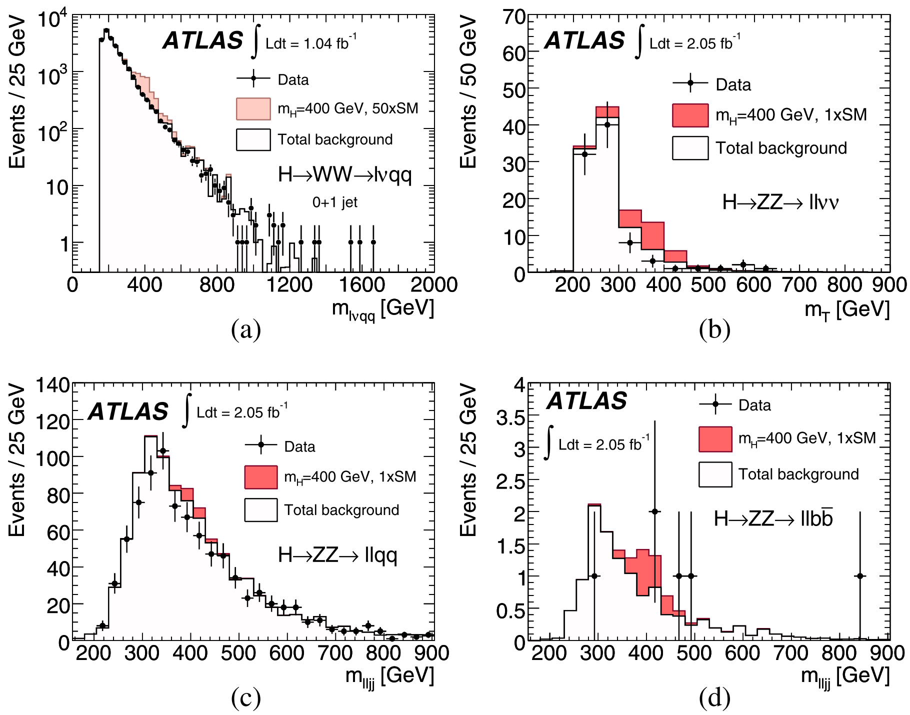

Fig. 2. Distributions of the reconstructed invariant or transverse mass, in analyses relevant for the search of the Higgs boson at high mass, for selected candidate events, the total background and the signal ($m_H = 400$ GeV) expected for the given value of m_H in the $H \to WW \to \ell\nu q\bar{q}'$ channel (a), the $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ channel (b) and the $H \to ZZ \to \ell^+\ell^- q\bar{q}$ channel for events selected in the b-jet untagged (c) and the tagged (d) categories. The signal distribution is displayed in a lighter red colour in the $H \to WW \to \ell\nu q\bar{q}'$ channel where it has been scaled up by a factor 50. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

mass constraint improves the mass resolution of the $\ell\ell qq$ system by approximately 10%. The number of events selected in the data with the low m_H (high m_H) untagged search is 21 000 (851) where 21 370 ± 310 (920 ± 100) are expected from the background, and 67 ± 11 (21.1 ± 0.8) from a signal with $m_H = 200$ GeV ($m_H = 400$ GeV). For the tagged search, the number of observed events in the data with the low m_H (high m_H) selection is 145 (6), in reasonable agreement with the 165 ± 22 (11.6 ± 1.9) expected from the background, while 4.4 ± 1.2 (2.1 ± 3.4) are expected from a signal with $m_H = 200$ GeV ($m_H = 400$ GeV). The invariant mass is used as the discriminating variable and its distribution is shown in Figs. 2(c) and 2(d) for the two categories.

3. Systematic uncertainties

The sources of systematic uncertainties, and their effects on the signal and background yields and shapes in each individual channel, are described in detail in Refs. [9–14]. In the combination, systematic uncertainties are considered either as fully correlated or uncorrelated. Partial correlations are treated by separating a given source into correlated and uncorrelated components. The effect of each uncertainty is estimated independently for each channel. The dominant correlated systematic uncertainties are those on the measurement of the integrated luminosity and on the theoretical predictions of the signal production cross sections and decay branching fractions, as well as those related to detector response that impact the analyses through the reconstruction of electrons, photons, muon, jets, magnitude of the missing transverse momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$) 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 of the samples used in each specific channel [16,17]. The uncertainty is larger for the last part of the 2011 data due to an increase in the average number of proton–proton interactions occurring in the same bunch crossing (pileup events).

The Higgs boson production cross sections are computed up to Next-to-Next-to-Leading Order (NNLO) [18–23] in QCD for the gluon fusion ($gg \to H$) process, including soft-gluon resummations up to Next-to-Next-to-Leading Log (NNLL) [24,25] and Next-to-Leading Order (NLO) electroweak (EW) corrections [26,27]. These results are compiled in Refs. [28–30]. The cross section for the vector-boson fusion ($qq' \to qq'H$) process is estimated at NLO [31–33] and approximate NNLO QCD [34]. The associated WH/ZH production processes ($q\bar{q} \to WH/ZH$) are computed at NLO [35,36] and NNLO [37]. The associated production with a $t\bar{t}$ pair ($q\bar{q}/gg \to t\bar{t}H$) is estimated at NLO [38–41]. The Higgs boson production cross sections, decay branching ratios [42–45] and their related uncertainties are compiled in Ref. [46]. The QCD scale uncertainties for $m_H = 120$ GeV amount to $^{+12}_{-8}$% for the $gg \to H$ process, ±1% for the $qq' \to qq'H$ and associated WH/ZH processes, and $^{+3}_{-9}$% for the $q\bar{q}/gg \to t\bar{t}H$ process. The uncertainties related to the parton distribution functions (PDF) for low m_H hypotheses typically amount to ±8% for the predominantly gluon-initiated processes $gg \to H$ and $q\bar{q}/gg \to t\bar{t}H$, and ±4% for the predominantly quark-initiated $qq' \to qq'H$ and WH/ZH processes [47–50]. The theoretical uncertainty associated with the exclusive Higgs boson production process with one additional jet in the $H \to WW^{(*)} \to \ell^+\nu\ell'^-\bar{\nu}$ channel amounts to ±20% and is treated according to the prescription of Refs. [51–53]. 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 $150\% \times (m_H/\mathrm{TeV})^3$ [53–56].

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 for muons; jet energy scale (JES) and jet energy resolution, which include a specific treatment for b-jets; contributions to the E_T^{miss} uncertainties uncorrelated with the JES; b-tagging and b-veto. 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 $H \to WW \to \ell\nu q\bar{q}'$ and $H \to ZZ \to \ell^+\ell^- q\bar{q}$. The electron and muon energy scales are directly constrained by $Z \to e^+e^-$ and $Z \to \mu^+\mu^-$ 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 limits

The signal strength, μ, is defined as $\mu = \sigma/\sigma_{SM}$, where σ is the Higgs boson production cross section being tested and σ_{SM} its SM value; it is a single factor used to scale all signal production processes for a given m_H hypothesis. The combination procedure of Refs. [52,57,58] is based on the profile likelihood ratio test statistic $\lambda(\mu)$ [59], 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 method [60] and a value of μ is regarded as excluded at the 95% (99%) CL when CL_s takes on the corresponding value.

The combined 95% CL exclusion limits on μ are shown in Fig. 3(a) as a function of m_H. These results are based on the asymptotic approximation [59]. The observed and expected limits using this procedure have been validated using ensemble tests and a Bayesian calculation of the exclusion limits with a uniform prior on the signal cross section. These approaches agree with the asymptotic median results to within a few percent. The expected 95% CL exclusion region covers the m_H range from 124 GeV to 519 GeV. The observed 95% CL exclusion regions are from 131 GeV to 238 GeV and from 251 GeV to 466 GeV. The regions between 133 GeV and 230 GeV and between 260 GeV and 437 GeV are excluded at the 99% CL. A deficit of events is observed in two m_H regions. At very low masses a local deficit in the diphoton channel allows an additional small mass range between 112.9 GeV and 115.5 GeV to be excluded at the 95% CL. Small deficits in various high-mass channels lead to observed limits for masses between 300 GeV and 400 GeV that are stronger than expected. The local probability of such a downward fluctuation of a background-only experiment corresponds to a significance of approximately 2.5σ. The probability to observe such a downward fluctuation over the full inspected mass range in the absence of a signal, using the method described in Section 5 [61], is estimated to be approximately 30%.

The observed exclusion covers a large part of the expected exclusion range, with the exception of the low and high m_H regions where excesses of events above the expected background are observed in various channels, and in a small mass interval around 245 GeV, which is not excluded due to an excess mostly in the $H \to ZZ^{(*)} \to \ell^+\ell^-\ell'^+\ell'^-$ channel.

5. Significance of the excess

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 a high-resolution invariant mass for fully reconstructed

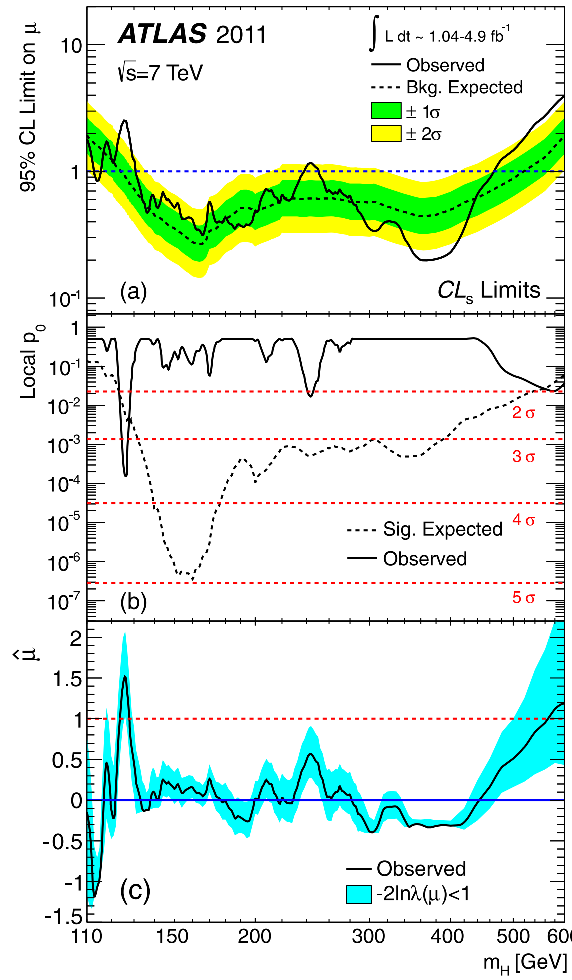

Fig. 3. (a) The combined 95% CL upper limits on the signal strength as a function of m_H; the solid curve indicates the observed limit and the dotted curve illustrates the median expected limit in the absence of a signal together with the $\pm 1\sigma$ (dark) and $\pm 2\sigma$ (light) bands. (b) The local p_0 as a function of the m_H hypothesis. The dashed curve indicates the median expected value for the hypothesis of a SM Higgs boson signal at that mass. The four horizontal dashed lines indicate the p_0 values corresponding to significances of 2σ, 3σ, 4σ and 5σ. (c) The best-fit signal strength as a function of the m_H hypothesis. The band shows the interval around $\hat{\mu}$ corresponding to region where $-2\ln\lambda(\mu) < 1$.

candidates. The $H \to WW^{(*)} \to \ell^+\nu\ell'^-\bar{\nu}$ channel as well has a broad excess of events in the transverse mass distribution as seen in Fig. 1(d).

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% [52,58,59].

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. [52,61].

The observed local p_0 values, calculated using the asymptotic approximation [59], 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. 3(b) in the entire search mass range and in Fig. 4 for the individual channels and their combination in the low mass range. Numerically consistent results are obtained using ensemble tests.

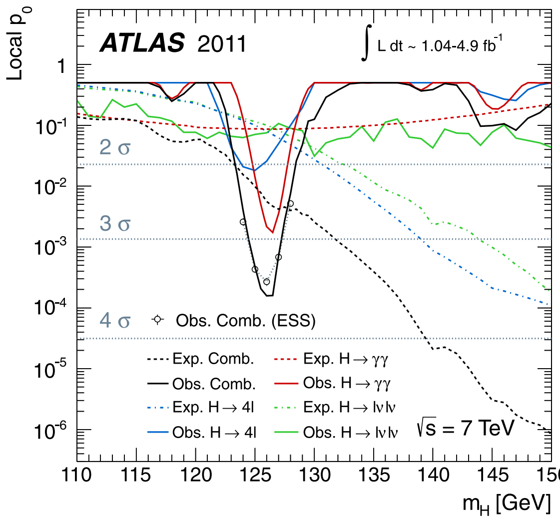

Fig. 4. The local probability p_0 for a background-only experiment to be more signal-like than the observation. The solid curves give the individual and combined observed p_0, estimated using the asymptotic approximation. The dashed curves show the median expected value for the hypothesis of a SM Higgs boson signal at that mass. The three horizontal dashed lines indicate the p_0 corresponding to significances of 2σ, 3σ, and 4σ. The points indicate the observed local p_0 estimated using ensemble tests and taking into account energy scale systematic uncertainties (ESS).

The largest local significance for the combination is achieved for $m_H = 126$ GeV, where it reaches 3.6σ with an expected value of 2.5σ for a SM signal. The observed (expected) local significance for $m_H = 126$ GeV is 2.8σ (1.4σ) in the $H \to \gamma\gamma$ channel, 2.1σ (1.4σ) in the $H \to ZZ^{(*)} \to \ell^+\ell^-\ell'^+\ell'^-$ channel, and 1.4σ (1.4σ) in the $H \to WW^{(*)} \to \ell^+\nu\ell'^-\bar{\nu}$ channel.

The significance of the excess is mildly sensitive to systematic uncertainties on the energy scale (herein referred to as ESS) 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 computed using ensemble tests. The results are displayed in Fig. 4 as a function of m_H. The observed effect of the ESS uncertainty is small and reduces the maximum local significance from 3.6σ to 3.5σ.

The global p_0 of a local excess depends on the range of m_H and the channels considered. The global p_0 associated with a 2.8σ excess anywhere in the $H \to \gamma\gamma$ search domain 110–150 GeV is approximately 7%. A 2.1σ 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 p_0 for a combined 3.5σ excess to be found anywhere in the range from 114 GeV to 146 GeV is 0.6% (2.5σ). This mass interval corresponds to the region not excluded at 99% CL by the combination of Higgs boson searches at LEP [7] and the first LHC combined search [54]. For the full mass range from 110 GeV to 600 GeV, the global p_0 is 1.4% (2.2σ).

The best-fit value of μ, denoted $\hat{\mu}$, is displayed in Fig. 3(c) as a function of the m_H hypothesis. The bands around $\hat{\mu}$ illustrate the μ interval corresponding to $-2\ln\lambda(\mu) < 1$ and represent an approximate $\pm 1\sigma$ variation. When evaluating exclusion limits and significance, μ is not allowed to be negative; however, this restriction is not applied in Fig. 3(c), in order to illustrate the presence and extent of downward fluctuations. Nevertheless, the μ parameter is still bounded to prevent negative values of the probability density functions in the individual channels, and for negative $\hat{\mu}$ values close to the boundary, the $-2\ln\lambda(\mu) < 1$ region does not always reflect a 68% confidence interval. The excess observed for $m_H = 126$ GeV corresponds to $\hat{\mu}$ of approximately $1.5^{+0.6}_{-0.5}$, which is compatible with the signal expected from a SM Higgs boson at that mass $(\mu = 1)$.

6. Conclusions

A dataset of up to 4.9 fb^{-1} recorded in 2011 has been used to search for the SM Higgs boson with the ATLAS experiment at the LHC. Higgs boson masses between 124 GeV and 519 GeV are expected to be excluded at the 95% CL. The observed exclusion at the 95% CL ranges from 112.9 GeV to 115.5 GeV, 131 GeV to 238 GeV and 251 GeV to 466 GeV. An exclusion of the SM Higgs boson production at the 99% CL is achieved in the regions between 133 GeV and 230 GeV and between 260 GeV and 437 GeV.

An excess of events is observed in the $H \to \gamma\gamma$ and $H \to ZZ^{(*)} \to \ell^+\ell^-\ell'^+\ell'^-$ channels, for m_H close to 126 GeV, which is also supported by a broad excess in the $H \to WW^{(*)} \to \ell^+\nu\ell'^-\bar{\nu}$ channel. The observed local significances of the individual excesses are 2.8σ, 2.0σ and 1.4σ, respectively. The expected local significances of these channels, for a 126 GeV SM Higgs boson are, coincidentally, all $\sim 1.4\sigma$. The combined local significance of these excesses is 3.6σ. When the energy scale uncertainties are taken into account, the combined local significance is reduced to 3.5σ. The expected combined local significance in the presence of a SM Higgs boson signal at that mass is 2.5σ. The global probability for such an excess to be found in the full search range, in the absence of a signal, is approximately 1.4%, corresponding to 2.2σ.

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