Standard Model Higgs Boson Searches at ATLAS

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A search for the Standard Model Higgs boson in proton-proton collisions with the ATLAS detector at the Large Hadron Collider is presented in this document. The experimental results are based on data taken in 2011 and 2012 with an integrated luminosity of up to 4.9 fb^{-1} at $\sqrt{s} = 7$ TeV and up to 5.9 fb^{-1} at $\sqrt{s} = 8$ TeV. The search is performed in a mass range of 110 GeV to 600 GeV combining twelve different Higgs Boson decay channels. A Standard Model Higgs Boson is excluded at 95% confidence level within a mass range of 110 to 122.6 GeV and 129.7 to 558 GeV. An excess in data is seen at a mass of 126.5 GeV with a local significance of 5σ which is consistent with the production and decay of a Standard Model Higgs boson.

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1 Introduction

In the Standard Model of particle physics the Higgs mechanism is an elegant theory to explain the electroweak symmetry breaking and the missing mass terms for the vector bosons and fermions [1]. One of the main goals of the ATLAS experiment [2] at the Large Hadron Collider is to find the Higgs boson, a scalar particle, which is the physical consequence of this mechanism and whose mass m_H is a free parameter in the Standard Model. Constraints on the Higgs mass have been provided by previous experiments LEP [3] and Tevatron [4] and the first results of the LHC experiments ATLAS and CMS. First hints of a possible Standard Model Higgs-like signal around a mass of 126 GeV with a local significance of 3.5σ have been seen by ATLAS detector in a preliminary analysis of the 2011 data [5]. Similar hints have been seen by CMS [6].
The ATLAS data of proton proton collisions at a center of mass energy of $\sqrt{s} = 7$ TeV recorded in 2011 with an integrated luminosity of 4.9 fb^{-1} form the basis for the direct search of the Standard Model Higgs boson in all detectable decay channels. The most sensitive channels, $H \to \gamma\gamma$, $H \to ZZ \to \ell\ell\ell\ell$, $H \to WW \to \ell\nu\ell\nu$, include in addition the data taken in 2012 at a center of mass energy of $\sqrt{s} = 8$ TeV with an integrated luminosity of 5.9 fb^{-1}, at which the production cross section for the Higgs boson is 25 to 30 % higher. A detailed overview of all searches performed with ATLAS is given in these proceedings with focus on the most sensitive channels.

2 Higgs searches at the ATLAS experiment

The search for the Standard Model Higgs boson with the ATLAS detector is performed for twelve different decay channels which cover a mass range of 110 to 600 GeV. An overview of the exploited channels, the integrated luminosity on which the results are based and the considered

Table 1: Summary of the Higgs searches performed at the ATLAS experiment. Shown are the different decay channels, explored mass ranges, the integrated luminosities $\mathcal{L}$ and references for the analyses.

Channel	m_H range [GeV]	$\mathcal{L}$ [fb^{-1}]	Reference
$H \to \gamma\gamma$	110-150	4.9 + 5.9	[7,8]
$H \to ZZ^{(*)} \to \ell\ell\ell'\ell'$	110-600	4.8 + 5.8	[9,10]
$H \to ZZ \to \ell\ell\nu\nu$	200-600	4.7	[11]
$H \to ZZ \to \ell\ell q\bar{q}$	200-600	4.7	[12]
$H \to WW^{(*)} \to \ell\nu\ell\nu$	110-600	4.7 + 5.8	[13,14]
$H \to WW \to \ell\nu q\bar{q}$	300-600	4.7	[15]
$H \to \tau^+\tau^- \to \ell\ell 4\nu; \ell\tau_{\mathrm{had}} 3\nu; \tau_{\mathrm{had}}\tau_{\mathrm{had}}\nu\nu$	110-150	4.7	[16]
$VH \to b\bar{b} \to \ell\nu b\bar{b}; \ell\ell b\bar{b}; \nu\nu b\bar{b}$	110-130	4.7	[17]

mass ranges is shown in Table 1. The searches in the individual channels are presented in the following.

2.1 High mass searches

- $H \to WW \to \ell\nu q\bar{q}$
  This analysis is split into six different subchannels depending on the number of additional jets and the lepton flavour [15]. The invariant mass of lepton, neutrino and two jets can be completely reconstructed under the constraint that $m_{\ell\nu}$ is equal to the mass of the W boson. Based on this mass distribution the limit is extracted for a mass range between 300 and 600 GeV. The best sensitivity is reached for $m_H = 400$ GeV where the observed (expected) upper bound on the cross section at 95% CL is 1.9 (1.6) times the cross section of the Standard Model (σ_{SM}).

- $H \to ZZ \to \ell\ell q\bar{q}$
  This search channel differentiates between the cases where exactly two or less than two jets have been tagged as b-jets [12]. The invariant mass is derived using the constraint that the dijet mass is equal to the Z boson mass and used as the discriminative variable for the limit extraction. This channel covers a mass range between 200 and 600 GeV, where no excess can be observed. An observed (expected) exclusion at 95 % CL of a mass range of 300 to 323 GeV and 353 to 410 GeV (351 to 404 GeV) is reached.

- $H \to ZZ \to \ell\ell\nu\nu$
  This channel provides a very high sensitivity at high masses [11]. Due to the high dependency on multiple proton collisions (pile-up) of the missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$) the analysis is split into two categories depending in the number of mean interactions. The mass cannot be fully reconstructed because of the two neutrinos, thus the transverse mass of $E_{\mathrm{T}}^{\mathrm{miss}}$ and the two leptons is used as discriminative variable. No excess can be observed in the mass range between 200 and 600 GeV. A broad mass range of a Higgs boson between 319 and 558 GeV (280 and 497 GeV) can be excluded with an observed (expected) upper limit at 95 % CL.

2.2 Low mass searches with low mass resolution

- $H \to WW^{(*)} \to \ell\nu\ell\nu$
  Due to the high branching ratio of this decay channel this search provides a high sensitivity in a wide mass range, but a low mass resolution [13]. The analysis is split into categories

of lepton flavour and jet multiplicity resulting from different Higgs production processes. To discriminate against the irreducible Standard Model WW decay the $\Delta\phi$ and invariant mass of the two leptons are used, which are expected to be small for a Higgs boson with spin 0. The transverse mass built from the two leptons and $E_{\mathrm{T}}^{\mathrm{miss}}$ is used as a discriminative variable. A first result was obtained with $\sqrt{s} = 7$ TeV data in 2011, where no excess of a possible Higgs boson in data could be observed in the investigated mass range from 110 to 600 GeV.
An update of the analysis has been done with additional 5.8 fb^{-1} of 2012 data at $\sqrt{s} =$ 8 TeV for the mixed lepon flavour channel [14]. Some adjustment in the event selections are made to increase the pile-up stability. With this additional data a broad excess with a maximum at 125 GeV can be observed, that is not compatible with a background only hypothesis. The local observed (expected) significance at this mass is measured to be 2.8σ (2.3σ) and the signal strength 1.4 ± 0.5. The transverse mass distribution for the one jet category and the exclusion limits at 95% CL are shown in Figure 1.

- $VH \to b\bar{b}$
To be able to obtain a significant separation of signal and background this Higgs decay channel is only studied for the case of the associated Higgs boson production with an additional vector boson [17]. Three cases are studied, the decay of the associated Z boson to two leptons, to two neutrinos and the decay of the associated W boson to a lepton and a neutrino. Analysis categories are formed for different kinematic phase space regions of the transverse momentum of the vector boson derived from the leptons and $E_{\mathrm{T}}^{\mathrm{miss}}$, respectively. Based on the invariant mass of the two b-jets an upper limit at 95% CL is extracted (see Figure 2, left). No excess is observed in the sensitive mass range between 110-130 GeV in the 2011 data at $\sqrt{s} = 7$ TeV.

- $H \to \tau^+\tau^-$
The search for Higgs decays to τ leptons is exploiting the different decay modes of τ leptons, thus the decay to two leptons, one lepton and one hadronic τ, two hadronic τ leptons, accompanied by two to four neutrinos [16]. Twelve different categories are studied which are based on different jet multiplicities and event topologies characteristic for the Higgs production processes like VBF or VH. The irreducible background of $Z \to \tau\tau$ is estimated from $Z \to \mu\mu$ data, where only the muons are replaced by simulated τ leptons and their decay products. The invariant mass of the two τ leptons is determined using the collinear approximation and the missing mass calculator [18], respectively. Based on this distribution an upper limit on the cross section is derived based on the $\sqrt{s} = 7$ TeV data of 2011. It lies between 2.9 and 11.7 $\times$ σ_{SM} in the relevant mass range between 110-150 GeV at 95 % CL, as can be seen in Figure 2 (right).

2.3 Low mass searches with high mass resolution

- $H \to ZZ^{(*)} \to \ell\ell\ell'\ell'$
This search channel features only a small branching ratio but a very high purity with a high signal to background ratio [9]. Since it only depends on the energy resolution of the leptons a very high mass resolution can be achieved. The analysis is performed in four categories based on the different lepton flavour combinations. The irreducible background ZZ is estimated with Monte Carlo, while other backgrounds like Z+jets or $t\bar{t}$ are estimated in data control regions. The resolution of the invariant four lepton mass and the efficiency of the reconstruction and identification of leptons determine the maximum sensitivity of this analysis. Thus, the latest improvements of the analysis for an inclusion of 2012 data

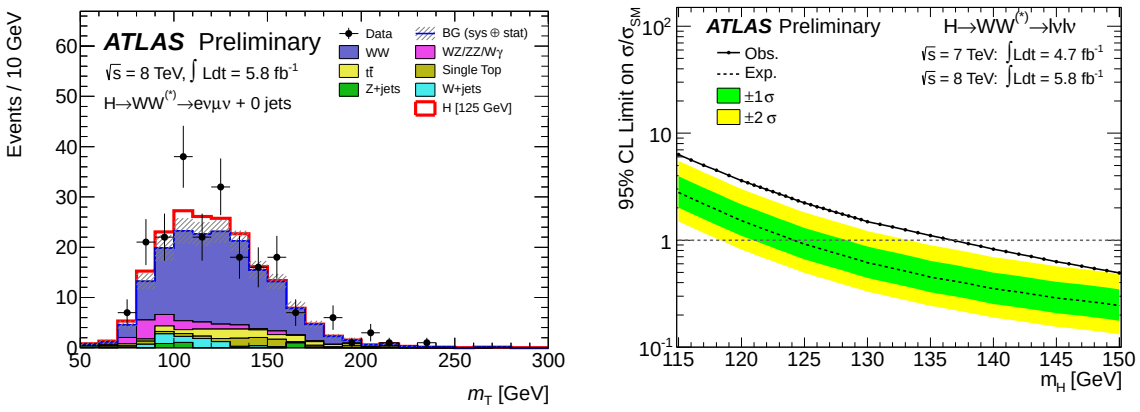

Figure 1: Left: Distribution of the transverse mass in 0 jet mixed flavour category of the $H \to WW \to \ell\nu\ell\nu$ search channel based on data taken at $\sqrt{s} = 8$ TeV. The expected signal for a SM Higgs boson with $m_H = 125$ GeV is added on top of the estimated total background [14]. Right: Observed (solid) and expected (dashed) exclusion limit at 95% CL as a function of m_H normalised to the Standard Model cross section for the $H \to WW \to \ell\nu\ell\nu$ decay based on a luminosity of 4.7 fb^{-1} of $\sqrt{s} = 7$ TeV data combined with 5.8 fb^{-1} of $\sqrt{s} = 8$ TeV data [14].

focus on these points [10]. A mass resolution of 1.8 to 2.5 GeV is reached. Lepton reconstruction which is robust against pile-up down to low transverse momenta was obtained with reconstruction and identification efficiency of above 95%.
Combining the data of 2011 (4.8 fb^{-1}) and 2012 (5.8 fb^{-1}) a broad mass range can be excluded by this search channel. The observed (expected) exclusion covers Higgs masses between 131 to 162 GeV and 170 to 460 GeV (124 to 164 GeV and 176 to 500 GeV). The invariant four lepton mass is shown in Figure 3 (left). 13 events are observed in data around a mass of 125 ± 5 GeV, while only 5.1 ± 0.8 background events are expected in this region. The observed (expected) 95% CL limit derived from this distribution (Figure 3, right) shows a clear excess at this mass with a local significance of 3.4σ (2.6σ). An excess is also consistently seen in the data of 2011 at $\sqrt{s} = 7$ TeV and 2012 at $\sqrt{s} = 8$ TeV are investigated separately.

- $H \to \gamma\gamma$
  Despite a very small branching ratio this search channel provides the highest sensitivity for the search of a Higgs boson with a low mass [7]. Two isolated photons with a high transverse energy are selected. The analysis is split into ten different categories. These are based on whether a conversion took place, different bins of detector region and the p_{T} thrust axis. The last category has been added only for 2012 to increase the sensitivity, it makes use of the event topology of the VBF Higgs production by requiring two additional jets [8].
  The several order of magnitudes higher background of diphoton, photon-jet and dijet processes has to be brought under control. The diphoton mass is used as a discriminative variable. It depends on the energy of the photons and the angle between them. Thus for this channel a good mass resolution and good jet rejection have to be provided, for which several improvements have been achieved for the analysis of 2012 data. A very good calorimeter energy measurement with a scale uncertainty of only 0.3 % and a pile-up robust algorithm to identify the primary vertex (photon pointing) result in a very good mass resolution of 1.6 to 3.1 GeV for the 2012 data. The invariant $m_{\gamma\gamma}$ spectrum is fit separately in each category with a Crystal ball and wide Gaussian parametrisation for the signal and various analytic functions for the background. The mass spectrum for a combination of all categories and the fit result can be seen in Figure 4 (left).

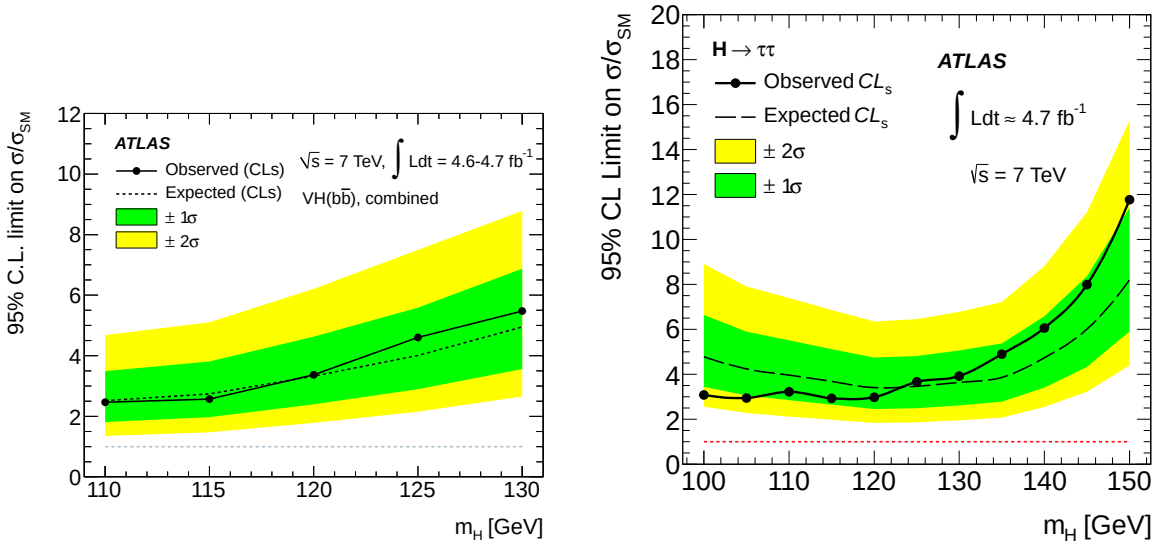

Figure 2: Left: Observed (solid) and expected (dashed) exclusion limit at 95% CL as a function of m_H normalised to the Standard Model cross section for the combined $VH \to b\bar{b}$ search channels based on a luminosity of 4.6-4.7 fb^{-1} of $\sqrt{s} = 7$ TeV data [17]. Right: Observed (solid) and expected (dashed) exclusion limit at 95% CL as a function of m_H for the combined $H \to \tau^+\tau^-$ search channels based on a luminosity of 4.7 fb^{-1} of $\sqrt{s} = 7$ TeV data [16].

In the derived 95% CL limit as a function of m_H (shown in Figure 4, right) an observed (expected) mass range of 112 to 122.5 GeV and 132 to 141 GeV (110 to 139.5 GeV) is excluded. A clear excess with respect to the background-only hypothesis can be observed in data with a maximum at 126.5 GeV, which occurs consistently in the 2011 and 2012 datasets at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV, respectively, with a local significance of 4.5 σ (expected 2.4 σ).

2.4 Combination

The results of the different search channels with 2011 data at $\sqrt{s} = 7$ TeV are statistically combined in addition with the results based on 2012 data $\sqrt{s} = 8$ TeV from the most sensitive channels $H \to \gamma\gamma$ and $H \to ZZ \to \ell\ell\ell\ell$ using a likelihood-based method [19,20] [a]. The exclusion limit at 95% CL for the full m_H range is shown in Figure 5 (left). Based on this data, an exclusion of masses from 110 to 582 GeV is expected without the presence of a SM Higgs boson. However the observed exclusion covers only a range of 110 to 122.6 GeV and 129.7 to 558 GeV, most of this range is even excluded at 99% CL.
Figure 5 (right) shows the local p_0 distribution, which quantifies the probability of a background fluctuation for a given mass. Over the full mass spectrum which is excluded in data a very good consistency with the background only hypothesis within 2σ can be observed. An excess with a minimum p_0 value of 3×10^{-7} at a mass of 125.6 GeV is seen in data. The local observed significance is 5σ, the expected one 4.6σ. Taking into account the look elsewhere effect [21] over the full mass range of 110 to 600 GeV yields a significance of 4.1σ. The combination of all channels yields a signal strength of $\mu = 1.2 \pm 0.3$, consistent with the SM expectation of $\mu = 1$. Figure 6 (left) compares the results separately for all channels, where a consistent excess can be seen in the two most sensitive channels $H \to \gamma\gamma$ and $H \to ZZ \to \ell\ell\ell\ell$.

[a] A combination with the updated $H \to WW \to \ell\nu\ell\nu$ result including also 2012 data was not ready at the time of the conference.

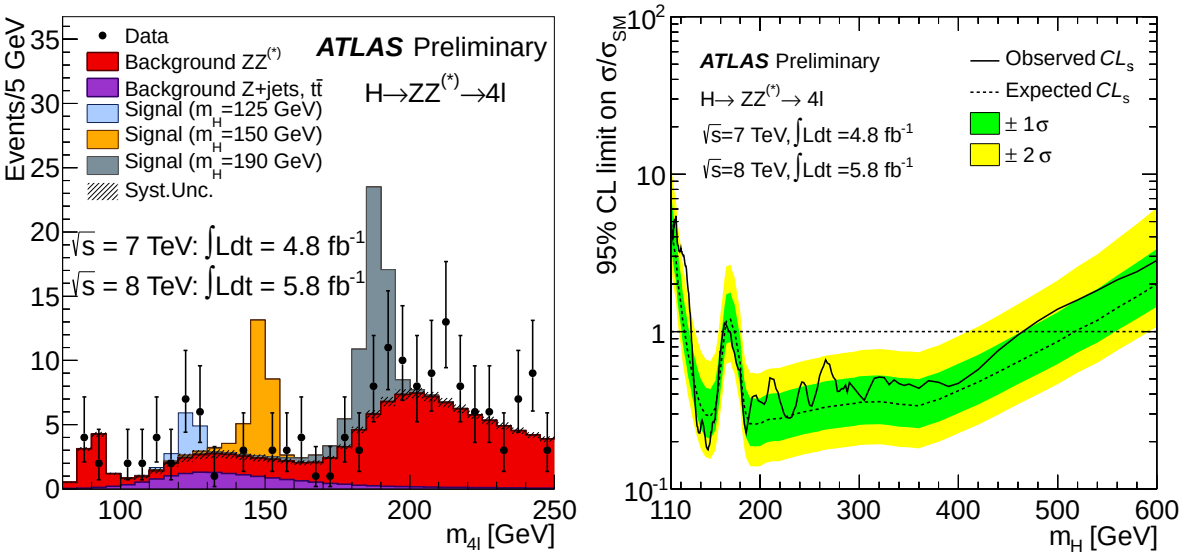

Figure 3: Left: Distribution of the invariant four-lepton mass for the candidates selected in the $H \to ZZ \to \ell\ell\ell\ell$ search in the low mass range for the combined datasets of $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV. The signal expectation for several m_H hypotheses is also shown [10]. Right: Observed (solid) and expected (dashed) exclusion limit at 95% CL as a function of m_H normalised to the Standard Model cross section for the $H \to ZZ \to \ell\ell\ell\ell$ decay based on a luminosity of 4.8 fb^{-1} of $\sqrt{s} = 7$ TeV data combined with 5.8 fb^{-1} of $\sqrt{s} = 8$ TeV data [10].

Figure 6 (right) shows two-dimensional contour plots for the individual channels $H \to \gamma\gamma$, $H \to ZZ \to \ell\ell\ell\ell$ and $H \to WW \to \ell\nu\ell\nu$ based on the results from 2011 and 2012 when both m_H and μ are floated in the likelihood fit [14]. One can see that the best-fit masses are consistent in all three channels.

3 Summary

A search for the Standard Model Higgs boson has been performed with the ATLAS detector in twelve different decay channels within a mass range of 110 to 600 GeV. The results are based on the full 2011 data at $\sqrt{s} = 7$ TeV with an integrated luminosity of up to 4.9 fb^{-1} and have been updated with 2012 data at $\sqrt{s} = 8$ TeV with up to 5.9 fb^{-1} for the most sensitive channels $H \to \gamma\gamma$ and $H \to ZZ \to \ell\ell\ell\ell$. A wide mass range is excluded at 95 % CL. An excess is observed around a mass of 126.5 GeV, which corresponds to a local significance of 5σ consistent with a Standard Model Higgs boson. These results are also consistently seen in the independent channels $H \to \gamma\gamma$ and $H \to ZZ \to \ell\ell\ell\ell$ with local significances of 4.5σ and 3.4σ. In addition, a recent update of the $H \to WW \to \ell\nu\ell\nu$ channel with 2012 data at $\sqrt{s} = 8$ TeV finds a consistent excess with a local significance of 2.8 GeV.

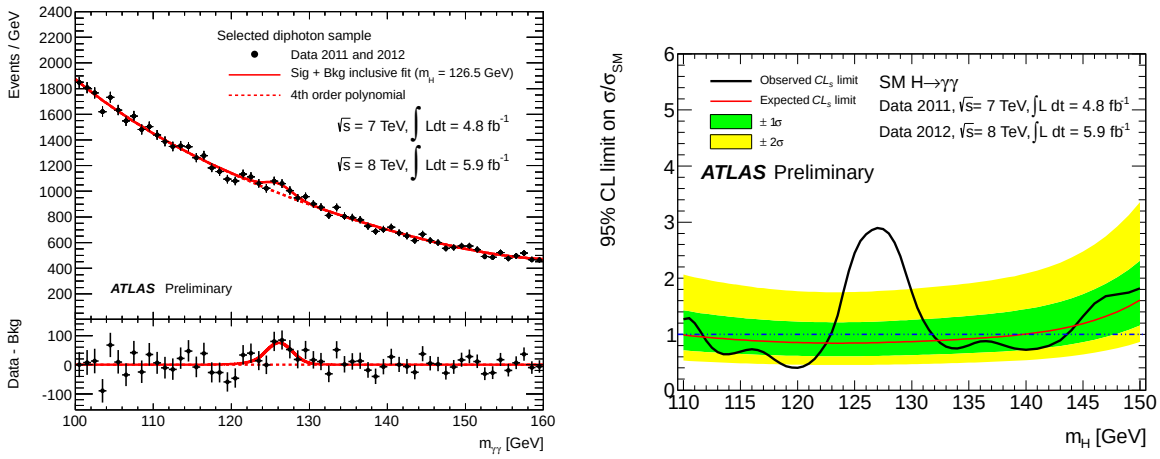

Figure 4: Left: Invariant diphoton mass distribution for the combined $\sqrt{s} = 7$ TeV and $\sqrt{s} = = 8$ TeV data samples for the $H \to \gamma\gamma$ search channel, overlaid with the total background obtained the sum of the fitted background-only models in the individual categories. The SM Higgs boson expectation for a mass hypothesis of 126.5 GeV is also shown[8]. Right: Observed (solid) and expected (dashed) exclusion limit at 95% CL as a function of m_H normalised to the Standard Model cross section for the $H \to \gamma\gamma$ search channel based on a luminosity of 4.8 fb^{-1} of $\sqrt{s} = 7$ TeV data combined with 5.9 fb^{-1} of $\sqrt{s} = 8$ TeV data[8].

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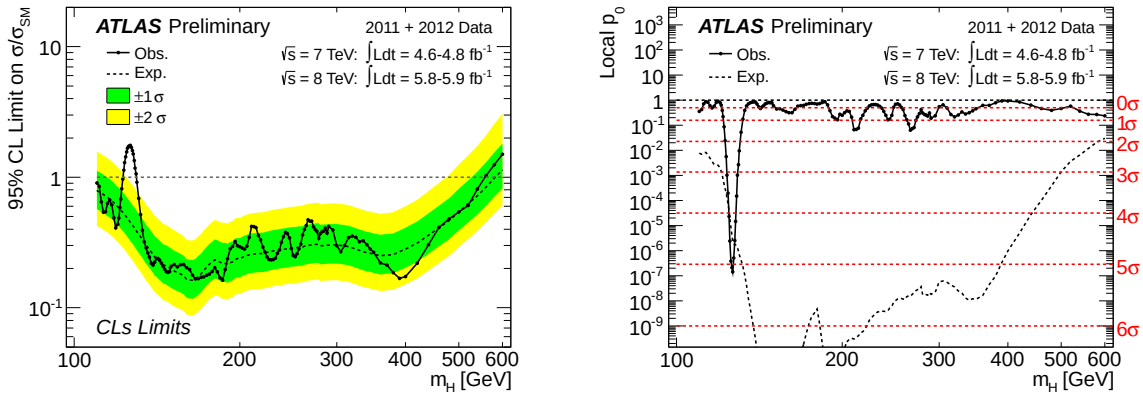

Figure 5: Left: Observed (solid) and expected (dashed) exclusion limit at 95% CL normalised to the Standard Model cross section shown for the full exploited mass range and the combination of all search channels at ATLAS based on a luminosity of 4.8 fb^{-1} of $\sqrt{s} = 7$ TeV data combined with 5.9 fb^{-1} of $\sqrt{s} = 8$ TeV data [20]. Right: Local probability p_0 of the compatibility with the background-only hypothesis for all search channels and the combined results of 2011 at $\sqrt{s} = 7$ TeV and 2012 at $\sqrt{s} = 8$ TeV. The value expected at the presence of a SM Higgs boson of mass m_H is also shown [20].

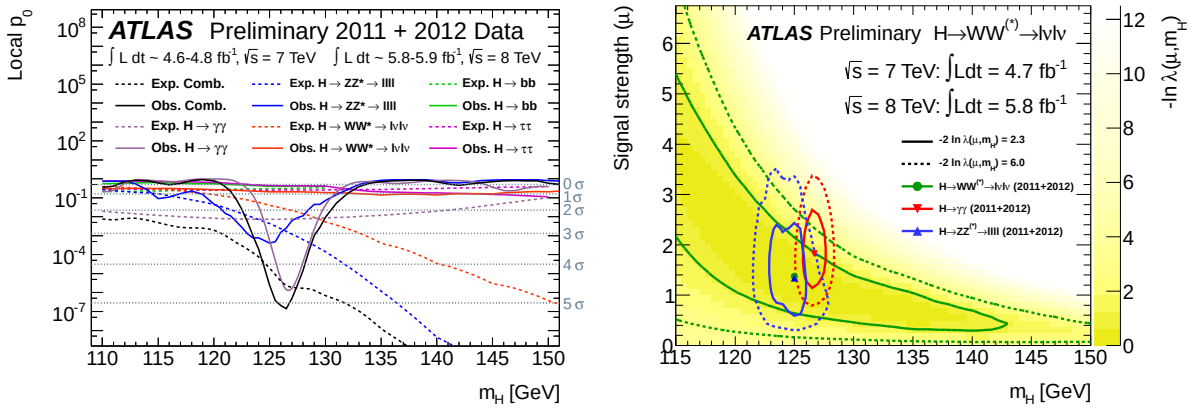

Figure 6: Left: Local probability p_0 of the compatibility with the background-only hypothesis separately for all search channels at ATLAS that enter the combined results of 2011 at $\sqrt{s} = 7$ TeV and 2012 at $\sqrt{s} = 8$ TeV. The value expected at the presence of a SM Higgs boson of mass m_H is also shown [20]. Right: Approximate 68% and 95% two-dimensional likelihood contours as a function of the the best-fit signal strength μ and m_H for the $H \to \gamma\gamma$, $H \to ZZ \to \ell\ell\ell\ell$ and $H \to WW \to \ell\nu\ell\nu$ analyses using the 2011 and 2012 data. The yellow shading shows the -ln($\lambda(\mu,m_H)$) values $H \to WW \to \ell\nu\ell\nu$ [14].