Observation of an excess of events in the Higgs boson search in ATLAS

Robert D. Harrington[a,*], On behalf of the ATLAS Collaboration

[a] SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom

Abstract

A search for the Standard Model Higgs boson with the ATLAS experiment at the LHC is presented. The pp collisions datasets correspond to an integrated luminosity of up to 4.9 fb^{-1} collected at $\sqrt{s}$ = 7 TeV in 2011, and up to 5.9 fb^{-1} collected at $\sqrt{s}$ = 8 TeV in 2012. Searches for $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^{(*)}$, $H \rightarrow WW^{(*)}$, $H \rightarrow b\bar{b}$ and $H \rightarrow \tau^+\tau^-$ have been performed on the 2011 data, while $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^{(*)} \rightarrow 4l$ have been updated using both 2011 and 2012 data. The Standard Model Higgs boson has been excluded at 95% confidence level for masses in the range of 110 to 122.6 GeV and 129.7 to 558 GeV. An excess of events has been observed for a Higgs boson mass hypothesis near 126.5 GeV with a local significance of 5.0σ.

Keywords: LHC, ATLAS, Higgs, Observation

1. Introduction

The ATLAS detector [1] was built to observe a wide spectrum of events from proton-proton (pp) collisions produced at the Large Hadron Collider (LHC). In the Standard Model (SM) [2–4], electroweak symmetry breaking is provided by the Higgs mechanism, resulting in a new particle referred to as the Higgs boson [5–10]. While the production cross section and branching ratios can be determined for a given Higgs boson mass, m_H, the actual value of the Higgs boson mass is not known and the search must be performed over a wide range of Higgs boson masses. The combined LEP limit [11] excludes a SM Higgs boson with a mass below 114.4 GeV at 95% CL, so ATLAS searches are performed for Higgs boson masses over 100 GeV.

Searches for the SM Higgs boson are being performed by the ATLAS Collaboration in several search channels based on the decay modes of the Higgs boson, as well as decays of subsequent vector bosons and tau leptons. The search channels are further broken down according to lepton flavor, presence of additional jets, kinematic regions, and other factors to enhance the sensitivity. An overview of the search channels is given in Table 1.

For the analyses presented in this paper, the overall signal strength factor μ, which acts as a scale factor on the total rate of signal events, is determined for each Higgs boson mass hypothesis. The signal strength is defined such that $\mu = 0$ corresponds to background only, and $\mu = 1$ corresponds to the SM Higgs boson signal in addition to the background. The fitting procedure used for individual analyses and the combination [12–15] is based on the profile likelihood ratio test statistic $\lambda(\mu)$ [16]. The test statistic allows to extracts the signal strength from the full likelihood which includes systematic uncertainties and their correlations. Exclusion limits are based on the CL_s prescription [17] such that a value of μ is regarded as excluded at the 95% confidence level (CL) when CL_s is less than 5%.

In 2011, the LHC delivered to the ATLAS detector an integrated luminosity of 5.6 fb^{-1} of pp collisions at a centre-of-mass energy of 7 TeV. Between 4.6 and 4.9 fb^{-1} (depending on the data quality requirements of the specific channels) were used for 2011 analyses. These analyses performed on 2011 data were combined to report the indication of an excess with a mass near 126.5 GeV with a local significance of 2.0 standard deviations (σ) [12]. The global probability for the background to create an excess of this significance in the mass range of 110-600 GeV was estimated to be ~15%. The mass ranges from 110.0 to 117.5, 118.5 to 122.5, and 129 to 539 GeV were excluded at 95% CL.

As of July 2012, the LHC has delivered to the ATLAS detector an integrated luminosity of 6.6 fb^{-1} at a centre-of-mass energy of 8 TeV. The higher centre-of-mass energy gives greater sensitivity to Higgs analy-

* Speaker
Email address: `robert.duane.harrington.jr@cern.ch` (Robert D. Harrington)

ses since in most cases signal production cross sections increase more with higher centre-of-mass energy than background production cross sections. In addition, the instantaneous luminosities were higher in 2012 than in 2011, with peak luminosities almost double those of 2011 for the same 50 ns bunch spacing. Higher integrated luminosities give greater sensitivity, but they come with larger numbers of pp collisions per bunch crossing (pile-up). The $H \to \gamma\gamma$ was shown to be relatively insensitive to pile-up, while the $H \to ZZ^{(*)} \to 4l$ analysis has been improved to increase pile-up robustness. These analyses have been updated with 5.8 and 5.9 fb^{-1} of the 2012 8 TeV data, respectively.

2. 2011 High Mass Higgs Boson Searches

In 2011, searches were performed up to 600 GeV in the following channels: $H \to WW \to l\nu qq$, $H \to ZZ \to ll\nu\nu$ and $H \to ZZ \to llqq$. The combination [18] of all channels was expected to allow exclusion at a 95% confidence level (CL) from 120-560 GeV. The actual excluded range using 2011 data alone was 129.2 to 541 GeV. The combined exclusion plot is shown in Figure 1.

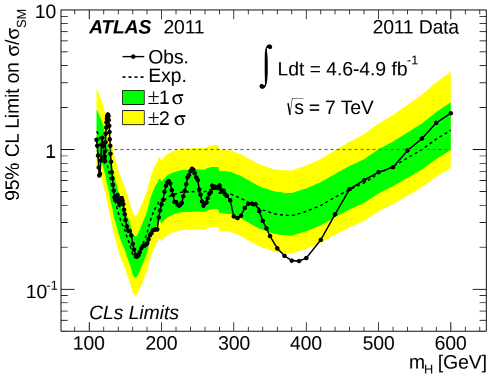

Figure 1: **2011 combination**. The observed (full line) and expected (dashed line) 95% CL combined upper limits on the SM Higgs boson production cross section divided by the SM expectation as a function of m_H in the full mass range considered. The dotted curves show the median expected limit in the absence of a signal and the green and yellow bands indicate the corresponding 68% and 95% intervals.[12]

3. 2011 VH, $H \to b\bar{b}$

$H \to b\bar{b}$ [19] is the dominant decay mode in the low mass range, but backgrounds are prohibitively large for searches for Higgs bosons produced by gluon fusion, $gg \to H \to b\bar{b}$. To enhance the signal-background ratio, the $H \to b\bar{b}$ analysis was restricted to Higgs boson production in association with a vector boson, WH or ZH, with the vector boson decaying to leptons. The analysis was performed in three channels based on the decay of the vector boson ($W \to l\nu$, $Z \to ll$, $Z \to \nu\nu$). Analyses used the transverse momentum of the vector boson or E_T^{miss} to enhance sensitivity. Fits to sidebands and control regions were used for background normalisations when possible, and likelihoods were formed from m_{bb} distributions. 4.6 to 4.7 fb^{-1} of 2011 data were analysed. No significant excess was found in the mass range 110-130 GeV (Figure 2), and an upper limit of 2.7 to 5.3 $\times\sigma_{SM}$ was set with 95% CL.

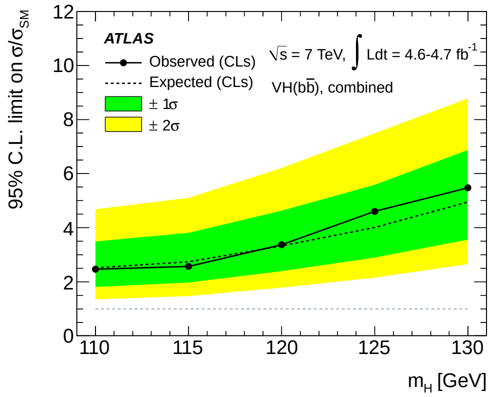

Figure 2: **VH,** $H \to b\bar{b}$**.** Expected (dashed) and observed (solid line) exclusion limits expressed as the ratio to the SM Higgs boson cross section, using the profile-likelihood method with CLs. The dark (green) and light (yellow) areas represent the 1 and 2 standard-deviation ranges of the expectation in the absence of a signal.[19]

4. 2011 $H \to \tau^+\tau^-$

$H \to \tau^+\tau^-$ [20] is a promising channel in spite of the low branching fraction. Three channels were analysed based on the decay of the τ leptons ($\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$), and these three channels were further subdivided with selections requiring jets to enhance the boost of the Higgs boson. Requiring a boosted Higgs boson aids in τ identification since the τ leptons are closer together, and τ decay products are more well collimated. 4.7 fb^{-1} of 2011 data were analysed. As shown in Figure 3, no significant excess was observed, and an upper limit was placed on Higgs boson production of 3.2 to 7.9 $\times\sigma_{SM}$ at 95% CL.

Table 1: Summary of the individual channels used in the combination. The transition points between separately optimised m_H regions are indicated when applicable. The symbols $\otimes$ and $\oplus$ represent direct products or sums over sets of selection requirements.

Higgs Decay	Subsequent Decay	Sub-Channels	m_H Range	$\mathcal{L}$ (fb^{-1})
$VH \to b\bar{b}$	$Z \to \nu\bar{\nu}$	$E_T^{miss} \in$ {120-160, 160-200, ≥200 GeV}	110-130	4.6
	$W \to l\nu$	$p_T^W \in$ {<50,50-100, 100-200, ≥200 GeV}		4.7
	$Z \to ll$	$p_T^W \in$ {<50,50-100, 100-200, ≥200 GeV}		4.7
$H \to \tau^+\tau^-$	$\tau_{lep}\tau_{lep}$	$\{eu\} \otimes$ {0-jets} $\otimes \{ll\} \oplus$ {1-jet,2-jets,VH}	100-150	4.7
	$\tau_{lep}\tau_{had}$	$\{e,\mu\} \otimes$ {0-jets} $\otimes$ {E_T^{miss}<20,E_T^{miss}≥20 GeV} $\oplus \{e,\mu\} \otimes$ {1-jet} $\otimes \{l\} \otimes$ {2-jets}		
	$\tau_{had}\tau_{had}$	{1-jet}		
$H \to WW^{(*)}$	$l\nu l\nu$	$\{ee, e\mu, \mu\mu\} \otimes$ {0-jets,1-jet,2-jets} $\otimes$ {low,high pile-up}	110-600	4.7
	$l\nu qq'$	$e, \mu \otimes$ {0-jets,1-jet,2-jets}	300-600	4.7
$H \to \gamma\gamma$	-	$\{p_{T_t} \otimes \eta_\gamma \otimes$ conversion} $\oplus$ {VBF}	110-150	4.9+5.9
$H \to ZZ^{(*)}$	$llll$	$\{4e, 2e2\mu, 2\mu 2e, 4e\}$	110-600	4.8+5.8
	$ll\nu\bar{\nu}$	$\{ee, \mu\mu\} \otimes$ {low,high pile-up}	200-280-600	4.7
	$llqq$	{b-tagged, untagged}	200-300-600	4.7

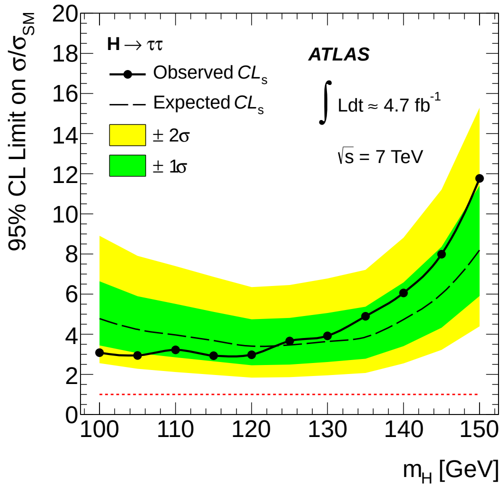

Figure 3: $H \to \tau^+\tau^-$. Expected (dashed) and observed (solid line) exclusion limits expressed as the ratio to the SM Higgs boson cross section, using the profile-likelihood method with CLs. The dark (green) and light (yellow) areas represent the 1 and 2 standard-deviation ranges of the expectation in the absence of a signal.[20]

5. 2011 $H \to WW^{(*)} \to l\nu l\nu$

The $H \to WW^{(*)} \to l\nu l\nu$ [21] analysis is sensitive over the entire range of 110-600 GeV. For this channel, only W bosons decaying to electrons and/or muons were considered. Backgrounds were normalised to data when possible. The Higgs boson transverse mass, calculated directly from lepton p_T and E_T^{miss}, was used for the likelihood fit. To enhance sensitivity, events were separated into different categories in the likelihood fit based on the number of jets. 4.7 fb^{-1} of 2011 data were analysed. As shown in Figure 4, no significant excess was observed. A SM Higgs boson with mass in the range of 133-261 GeV was excluded with 95% CL.

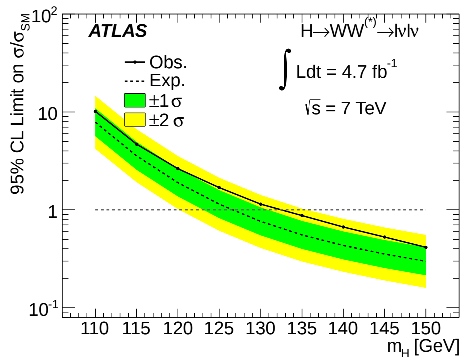

Figure 4: $H \to WW^{(*)} \to l\nu l\nu$. Expected (dashed) and observed (solid line) exclusion limits expressed as the ratio to the SM Higgs boson cross section, using the profile-likelihood method with CLs. The dark (green) and light (yellow) areas represent the 1 and 2 σ ranges of the expectation in the absence of a signal.[21]

6. 2011+2012 $H \to ZZ^* \to 4$ leptons

The $H \to ZZ^* \to 4l$ analysis [22] was updated with 2012 data for a total of 4.8 fb^{-1} of 7 TeV data and 5.8 fb^{-1} of 8 TeV data. The likelihood was constructed using m_{4l} distributions for signals and backgrounds. Templates were taken from Monte Carlo simulation for the four signal contributions ($gg \to H$, VBF, WH, ZH) and the $ZZ^{(*)}$ background. Shapes were taken from control regions in data for the $t\bar{t}$, Z+jets and $Zb\bar{b}$ backgrounds and normalised to data. Four categories were used based on the invariant mass of the lepton pairs and their flavour (electrons or muons). Figure 5 shows the fit of the data to the m_{4l} templates for signal at 3 values of m_H and backgrounds for all categories combined.

The analysis was improved over the 2011 analysis [23] through changes to selection cuts and electron reconstruction and identification to improve the sensitivity by 20-30%. The resulting exclusion range was 131-162 and 170-460 GeV at 95% CL. An excess was observed at 125 GeV with a local significance of 3.4σ, and a global significance of 2.5σ taking into account the look-elsewhere effect over the range 110-141 GeV (Figure 6). The fitted signal strength at 125 GeV was $\mu = 1.3 \pm 0.6$.

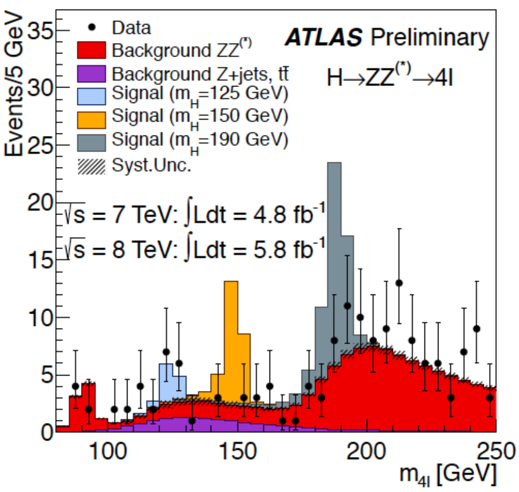

Figure 5: $H \rightarrow ZZ^{(*)} \rightarrow 4l$. The distribution of the four-lepton invariant mass, m_{4l}, for the selected candidates compared to the background expectation for the 80-250 GeV mass range for the combined $\sqrt{s}$=8 TeV and $\sqrt{s}$=7 TeV datasets. Error bars represent 68.3% central confidence intervals. The signal expectation for several m_H hypotheses is also shown.[22]

7. 2011+2012 $H \rightarrow \gamma\gamma$

The $H \rightarrow \gamma\gamma$ search [24] was performed in the mass range 110 to 150 GeV using integrated luminosities of 4.9 fb^{-1} of 7 TeV 2011 data and 5.9 fb^{-1} of 8 TeV 2012 data. Nine categories were used in the likelihood based on the pseudorapidity of each photon, whether it was reconstructed as a converted or unconverted photon, and the di-photon momentum transverse to the diphoton thrust axis. A tenth category was used requiring 2 jets to enhance the contribution from vector boson fusion (VBF). The shape of the $m_{\gamma\gamma}$ distribution for the signal component of the likelihood was modelled with the sum

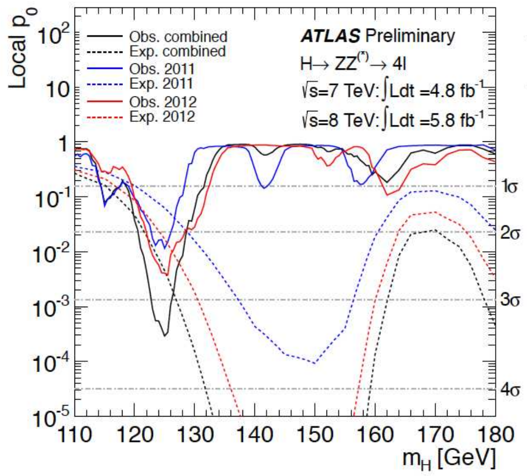

Figure 6: $H \rightarrow ZZ^{(*)} \rightarrow 4l$. The observed local p0 for the combination of the 2011 and 2012 datasets (solid black line); the $\sqrt{s}$=7 TeV and $\sqrt{s}$=8 TeV data results are shown in solid lines (blue and red, respectively). The dashed curves show the expected median local p0 for the signal hypothesis when tested at the corresponding m_H. The horizontal dashed lines indicate the p0 values corresponding to local significances of 1σ, 2σ, 3σ and 4σ. [22]

of a Crystal Ball and Gaussian fit to Monte Carlo simulation. The background likelihood shapes were data-driven and modelled, depending on the category, as an exponential function, a fourth-order polynomial or an exponential function of a second-order polynomial. Figure 7 shows the level of agreement between the data and the signal + background model for all categories combined. The ranges 112-122.5 and 132-143 GeV were excluded with 95% CL, and an excess was observed at 126.5 GeV with a local significance of 4.5σ (Figure 8) and a fitted signal strength of $\mu = 1.9 \pm 0.5$. The global significance taking into account the look-elsewhere effect over the range 110-150 GeV was 3.6σ.

8. Combined Results

The 2011 results for all channels, as well as the updated results using 2011 and 2012 data for $H \rightarrow ZZ^{(*)} \rightarrow 4l$ and $H \rightarrow \gamma\gamma$, were combined [25] to give an exclusion in the ranges of 110 to 122.6 GeV and 129.7 to 558 GeV at 95% CL (Figure 9). An excess was observed at 126.5 GeV with a local significance of 5.0σ (Figure 10). The best-fit value of signal strength was $\mu = 1.2 \pm 0.3$ (Figure 11). The global significance taking into account the look-elsewhere effect over the range of 110-600 (110-150) was 4.1(4.3)σ. Lastly, the $H \rightarrow ZZ^{(*)} \rightarrow 4l$ and $H \rightarrow \gamma\gamma$ channels were used to obtain the contour plots in Figure 12.

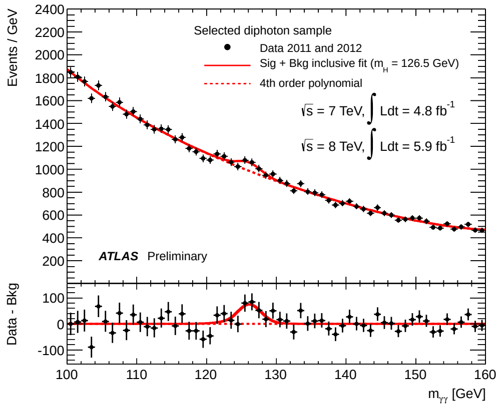

Figure 7: $H \to \gamma\gamma$. Invariant mass distribution for the combined $\sqrt{s}$=7 TeV and $\sqrt{s}$=8 TeV data samples. Superimposed is the result of a fit including a signal component fixed to a hypothesized mass of 126.5 GeV and a background component described by a fourth-order Bernstein polynomial. The bottom inset displays the residual of the data with respect to the fitted background.[24]

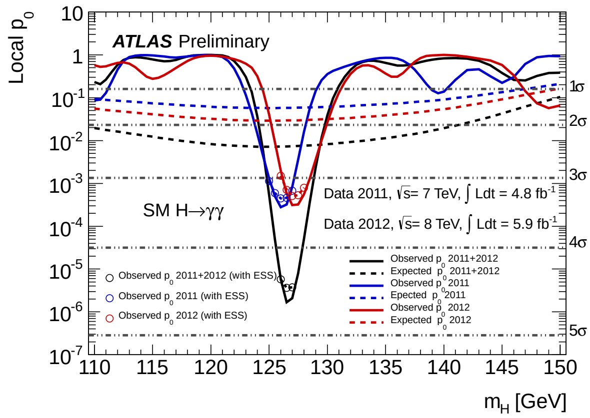

Figure 8: $H \to \gamma\gamma$. Expected and observed local p0 values for a SM Higgs boson as a function of the hypothesized Higgs boson mass mH for the combined analysis and for the $\sqrt{s}$=7 TeV and $\sqrt{s}$=8 TeV data samples separately. The observed p0 including the effect of the photon energy scale uncertainty on the mass position is included via pseudo-experiments and shown as open circles.[24]

9. Conclusion

Searches for the SM Higgs boson have been performed in the $H \to \gamma\gamma$, $H \to ZZ^{(*)}$, $H \to WW^{(*)}$, $H \to b\bar{b}$ and $H \to \tau^+\tau^-$ channels with up to 4.9 fb^{-1} of data taken in 2011 at $\sqrt{s}$ = 7 TeV. The $H \to \gamma\gamma$ and $H \to ZZ^{(*)} \to 4l$ analyses have been updated with up to 5.9 fb^{-1} of data taken in 2012 at $\sqrt{s}$ = 8 TeV. The new 2012 results were combined with the 2011 results to give an updated exclusion range. A 5σ excess has been observed at a mass near 126.5 GeV, with an expected significance of 4.6 σ. More data are needed to determine the nature of the newly observed resonance.

References

[1] ATLAS Collaboration, 2008 JINST 3 S08003.
[2] S. L. Glashow, Nucl. Phys. 22 (1961) 579588.
[3] S. Weinberg, Phys. Rev. Lett. 19 (1967) 12641266.
[4] A. Salam, in *Elementary Particle Theory: Relativistic Groups and Analyticity (Nobel Symposium No. 8)*. (Almqvist and Wiksell, Stockholm, 1968) p. 367.
[5] F. Englert and R. Brout, Phys. Rev. Lett. 13 (1964) 321323.
[6] P. W. Higgs, Phys. Lett. 12 (1964) 132133.
[7] P. W. Higgs, Phys. Rev. Lett. 13 (1964) 508509.
[8] G. Guralnik, C. Hagen, and T. Kibble, Phys. Rev. Lett. 13 (1964) 585587.
[9] P. W. Higgs, Phys. Rev. 145 (1966) 11561163.
[10] T. Kibble, Phys. Rev. 155 (1967) 15541561.
[11] ALEPH, DELPHI, L3 and OPAL collaborations and LEP Working Group for Higgs boson searches, Phys. Lett. **B 565** (2003) 6175.
[12] ATLAS Collaboration, Phys. Rev. D **86**, 032003 (2012).
[13] ATLAS Collaboration, Eur. Phys. J. **C71** (2010) 1728.
[14] ATLAS and CMS Collaborations, *LHC Higgs Combination Working Group Report*, ATL-PHYS-PUB-2011-011, CERN-CMS-NOTE-2011-005 (2011).
[15] L.Moneta, K.Belasco, K.S.Cranmer, S.Kreiss, A.Lazzaro, et al., PoS **ACAT2010** (2010) 057.
[16] G.Cowan, K.Cranmer, E.Gross and O.Vitells, Eur. Phys. J. **C71** (2010) 1554.
[17] A.L.Read, J.Phys **G28** (2002) 2693-2704.
[18] ATLAS Collaboration, *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*, ATLAS-CONF-2012-019 (2012).
[19] ATLAS Collaboration, *Search for the Standard Model Higgs boson produced in association with a vector boson and decaying to a b-quark pair with the ATLAS detector at the LHC*, submitted to Phys. Lett. B (2012), arXiv:1207.0210 [hep-ex].
[20] ATLAS Collaboration, *Search for the Standard Model Higgs boson in the* $H \to \tau^+\tau^-$ *decay mode in* $\sqrt{s}$ *= 7 Tev pp collisions with ATLAS*, JHEP **09** (2012) 070.
[21] ATLAS Collaboration, *Search for the Standard Model Higgs boson in the* $H \to WW^{(*)} \to W^+W^-$ *decay mode with 4.7 fb*$^{-1}$ *of ATLAS data at* $\sqrt{s}$ *= 7 TeV*, Phys.Lett. **B 716** (2012) 62-81.
[22] ATLAS Collaboration, *Observation of an excess of events in the search for the Standard Model Higgs boson in the* $H \to ZZ^{(*)} \to 4l$ *channel with the ATLAS detector*, ATLAS-CONF-2012-092 (2012).
[23] ATLAS Collaboration, *Search for the Standard Model Higgs boson in the decay channel* $H \to ZZ^{(*)} \to 4l$ *with 4.8 fb*$^{-1}$ *of pp collisions at* $\sqrt{s}$ *= 7 TeV with the ATLAS detector*, Phys. Lett. **B 710** (2012) 382-402.
[24] ATLAS Collaboration, *Observation of an excess of events in the search for the Standard Model Higgs boson in the* $\gamma\gamma$ *channel with the ATLAS detector*, ATLAS-CONF-2012-091 (2012).
[25] ATLAS Collaboration, *Observation of an Excess of Events in the Search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, ATLAS-CONF-2012-093 (2012).

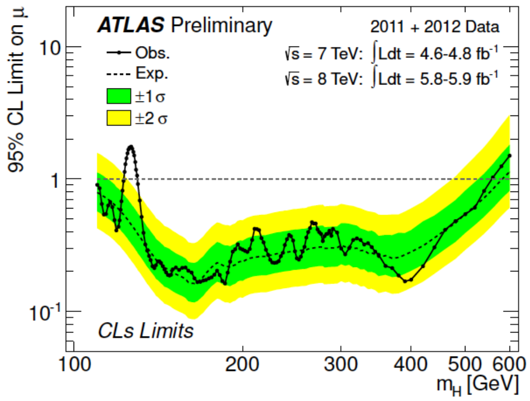

Figure 9: **2011+2012 combined**. The observed (full line) and expected (dashed line) 95% CL combined upper limits on the SM Higgs boson production cross section divided by the SM expectation as a function of m_H in the full mass range. The dashed curves show the median expected limit in the absence of a signal and the green and yellow bands indicate the 68% and 95% intervals.[25]

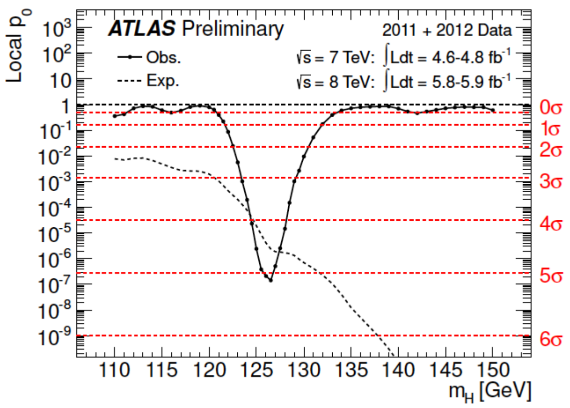

Figure 10: **2011+2012 combined**. The local probability p_0 for a background-only experiment to be more signal-like than the observation in the low mass range as a function of m_H. The dashed curves show the median expected local p_0 under the hypothesis of a SM Higgs boson production signal at that mass. The horizontal dashed lines indicate the p-values corresponding to significances of 1σ to 6σ.[25]

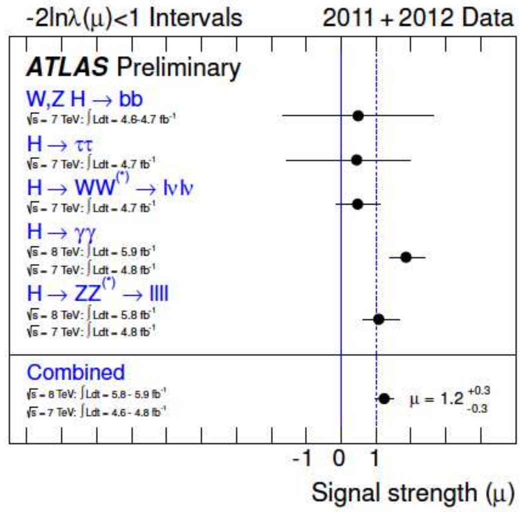

Figure 11: Summary of the individual and combined best-fit values of the strength parameter for a Higgs boson mass hypothesis of 126.5 GeV.[25]

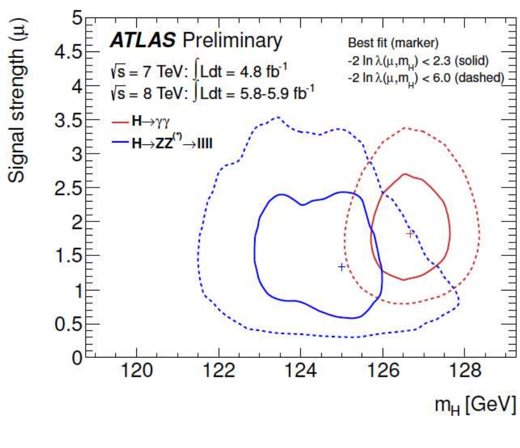

Figure 12: **2011+2012 combined**. Likelihood contours in (μ, m_H) for the $H \rightarrow ZZ^{(*)} \rightarrow l^+l^-l^+l^-$ and $H \rightarrow \gamma\gamma$ channels including energy scale systematics are shown in panel.[25]