SEARCH FOR ASSOCIATED PRODUCTION OF THE HIGGS BOSON IN THE $H \to WW$ CHANNEL WITH A FULLY LEPTONIC FINAL STATE*

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A search for the Higgs boson in the WH and ZH associated production modes, with $H \to WW^{(*)}$ and a fully leptonic final state with electrons or muons, is performed using data collected in 2012 with the ATLAS detector at the CERN Large Hadron Collider. The dataset corresponds to 20.7 fb^{-1} of proton–proton collision data at a center-of-mass energy of 8 TeV. The result obtained with the 2012 data is combined with a search for WH, with $H \to WW^{(*)}$ and a fully leptonic final state with electrons or muons, corresponding to 4.7 fb^{-1} of data recorded at a center-of-mass energy of 7 TeV.

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1. Introduction

On the 4$^{\text{th}}$ of July 2012, both the ATLAS [1] and CMS [2] experiments, announced the discovery of a boson with properties consistent with those expected from the Electroweak Symmetry Breaking model. After the discovery, the effort focused on the study of its properties with data acquired in 2011 and 2012. In this scenario, the study of the interactions between the Higgs boson and the Standard Model (SM) particles became interesting to verify its nature. The Higgs boson production in the WH and ZH associated modes, which will be referred to as the VH associated production, provides important information on the Higgs boson couplings to gauge bosons. Here, a review of the results on the Higgs boson

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production in the VH mode with $H \rightarrow WW^{(*)}$ channel, using the 2012 (2011) data collected with the ATLAS detector at $\sqrt{s} = 8$ TeV (7 TeV), is reported. The analyzed final states involve only W and Z bosons decaying to electrons and muons. For the SM Higgs boson with a mass of 125 GeV, the expected cross section times the branching ratios is 1.5 fb for $WH \rightarrow WWW \rightarrow l\nu l\nu l\nu$ and 0.3 fb for $ZH \rightarrow ZWW \rightarrow lll\nu l\nu$ (with $l = e, \mu$). The result obtained with data acquired by the ATLAS detector at a center-of-mass energy of 8 TeV for the WH production mode is combined with a previous search with 4.7 fb^{-1} of data collected in 2011 at $\sqrt{s} = 7$ TeV. To provide a complete description of the VH search, a combination of the $WH \rightarrow WWW \rightarrow l\nu l\nu l\nu$ result, which will be referred to as the 3-lepton analysis, and of the $ZH \rightarrow ZWW \rightarrow lll\nu l\nu$, hereafter called 4-lepton analysis, are presented. This result is combined with the search for $H \rightarrow WW^{(*)}$ through other production mechanisms, gluon–gluon fusion and vector boson fusion [3].

2. 3-lepton analysis

In this section, a study of the production of the Higgs boson in association with W boson with a fully leptonic final state is presented. Only muon and electron final states are considered. Data were collected in 2012 at $\sqrt{s} = 8$ TeV by the ATLAS experiment. The analysis goal is to study the WH production focusing on the Higgs boson mass hypothesis of 125 GeV. The analysis selects events with only three leptons, with a total charge of ± 1, and missing transverse momentum. The analysis has also some acceptance for the Higgs boson produced in association with Z boson as well as for the Higgs boson produced in association with W boson decaying to a pair of tau leptons. The 3-lepton analysis overlaps in a small phase space corner with the Higgs boson search in the $WW^{(*)}$ decay channel, hereafter called 2-lepton analysis. The overlap comes from events with exactly two leptons satisfying the tighter quality criteria presented in Ref. [3] and exactly one failing them but satisfying the selections of the WH analysis. The analysis presented was optimized for WH irrespectively from the overlap, but in order to allow a statistical combination of the results presented here with the 2-lepton analysis, the events in overlap were explicitly removed from the 3-lepton analysis. The event topology studied by this analysis is common to other physics processes, which represent the background to the WH signal. The background processes with three isolated real leptons are mainly SM diboson productions of $W\gamma^{(*)}$ and $WZ^{(*)}$, together with $ZZ^{(*)}$ production with an undetected lepton, and cannot be reduced by the application of tight lepton identification criteria. Due to the presence of one neutral particle (Z or γ), these backgrounds are usually characterized by the presence of at least one pair of the same flavor opposite sign (SFOS) leptons. To suppress these backgrounds and improve the sensitivity, the analysis distinguishes events with SFOS leptons from events without any such pair, in *Z-enriched* and *Z-depleted* samples, respectively. Final states with fewer than three prompt leptons and/or without real missing transverse momentum may contribute as background due to the presence of fake leptons and detector resolution effects. Fake leptons are defined both as misidentified leptons and as real leptons from light flavor, beauty and charm decays. Background processes with two prompt leptons, such as WW, Z and $t\bar{t}$ production, must be accompanied by a fake lepton to enter either the Z*-enriched* or Z*-depleted* samples. They can, therefore, be significantly reduced by isolation requirements on the leptons. At a significantly lower rate, but comparable with the signal, the triboson SM production (VVV), in particular the $WWW^{(*)}$ process, represents an irreducible background. To have a more compact description of the backgrounds the processes are organized in three categories:

- VV: diboson production. This is dominated by $WZ^{(*)}$ production. Minor contributions arise from $ZZ^{(*)}$, WW and $W\gamma$ productions.

- Fake leptons: dominated by $t\bar{t}$ and Z+jets events. Minor contributions come from W+jets production and single top quark produced through the s-channel or t-channel.

- VVV: triboson production. This is mainly $WWW^{(*)}$ with a minor contribution from $ZWW^{(*)}$.

The *Z-enriched* sample contains 3/4 of the signal, but suffers from all the backgrounds listed above, while the *Z-depleted* sample contains only 1/4 of the signal but is affected mainly by those backgrounds that are reducible through lepton identification and/or isolation criteria. Due to the different background composition of the *Z-enriched* and *Z-depleted* samples, the selection criteria are optimized separately. Helicity conservation in the decay of the two W bosons from a scalar Higgs boson leads, in general, to a small opening angle between the leptons originating from the Higgs boson decay, while the lepton from the decay of the recoiling W boson tends to be at a large angle with respect to the other two. For this reason, the leptons in the event are classified by identifying l_0 as the lepton with unique charge, l_1 as the lepton closer in $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$ to l_0, and l_2 as the remaining one. In most of the cases, l_0 and l_1 are the Higgs boson decay candidates. It is possible to discriminate between irreducible backgrounds and signal events using the opening angle between leptons.

2.1. 3-lepton analysis selections

The pre-selection requires events containing exactly three isolated leptons with $p_{\mathrm{T}} > 15$ GeV and a total charge ± 1. Events are accepted if at least one of these leptons matches an object responsible for firing the single-lepton trigger. After the pre-selection, the events are divided in *Z-enriched* and *Z-depleted* samples, with the *Z-enriched* sample further subdivided into $eee + \mu\mu\mu$ and $ee\mu + \mu\mu e$ samples which present a different ratio of signal over diboson background events, due to the different flavor combinations accessible in the final state. Due to the different background composition, the analysis selections are optimized separately for the *Z-enriched* and *Z-depleted* regions. However, due to the similar topology of the signal events in the two regions, several selections are equal in the *Z-enriched* and *Z-depleted.* In order to reduce the fake leptons background, in particular the $t\bar{t}$ background, events are required to contain at most one jet of transverse momentum above 25 GeV, which should not be b-tagged. Due to the presence of neutrinos in the fully leptonic final state of the $WH \to WWW^{(*)} \to l\nu l\nu l\nu$ channel, a selection on the missing transverse momentum is applied. The missing transverse momentum, $E_{\mathrm{T}}^{\mathrm{Miss}}$, is defined as the magnitude of the vector sum of the transverse momenta of the reconstructed objects. In the 3-lepton analysis, a modified definition of the missing transverse momentum is introduced in order to reduce the impact of mismeasurements of high-p_{T} leptons and jets on the total missing transverse momentum. The modified quantity, $E_{\mathrm{T,rel}}^{\mathrm{Miss}}$, is defined as

$$E_{\mathrm{T,rel}}^{\mathrm{Miss}} = E_{\mathrm{T}}^{\mathrm{Miss}} \sin \Delta\phi_{\min} \,, \tag{1}$$

with $\Delta\phi_{\min} \equiv \min(\Delta\phi, \frac{\pi}{2})$, where $\Delta\phi$ is the angle between the missing transverse momentum and the nearest lepton or jet which passed the pre-selection criteria. In order to suppress events with low missing transverse momentum, $E_{\mathrm{T,rel}}^{\mathrm{Miss}}$ is required to be above 25 GeV for the *Z-depleted* sample and above 40 GeV for the *Z-enriched* sample. In the *Z-enriched* region, the masses of all SFOS pairs are required to be at least 25 GeV away from the nominal Z mass. This requirement suppresses mainly the $WZ^{(*)}$ and $ZZ^{(*)}$ backgrounds. Due to the presence of $W\gamma^{(*)}$ and Drell–Yan events in both the *Z-depleted* and *Z-enriched* regions a lower cut is set on the smallest invariant mass of opposite sign leptons at 12 GeV, independently of their flavor. This selection reduces the $W\gamma^{(*)}$ and Drell–Yan backgrounds and rejects events from a region which could be populated by heavy flavor backgrounds. As previously described, a possible discriminant between signal and background events, in the case of the SM Higgs boson, is the opening angle between the leptons coming from the Higgs boson decay. The angular separation between l_0 and l_1, ΔR_{l0l1}, should be smaller than 2. Finally, to allow a combination with the other Higgs boson production mechanisms involving the $H \to WW^{(*)}$ events selected by the 2-lepton search, described in Ref. [3], are removed.

2.2. 3-lepton analysis result

The number of expected and observed events after the selections described in previous sections is shown in Table I.

TABLE I

Number of expected and observed events at several stages of the cutflow for the different signal regions of the 3-lepton analysis [4].

	VVV	VV	Fakes	Total bkg.	$VH(125)$	Data
3 leptons	19.5 ± 0.5	2410 ± 50	930 ± 100	3370 ± 150	18.53 ± 0.25	3717
Z-enriched ($eee + \mu\mu\mu$)	5.89 ± 0.18	1228 ± 23	380 ± 40	1620 ± 50	7.31 ± 0.17	1711
Jet multiplicity and b-veto	4.79 ± 0.19	1064 ± 24	273 ± 33	1350 ± 50	4.85 ± 0.13	1321
$E_{\mathrm{T,rel}}^{\mathrm{Miss}}$ cut	2.51 ± 0.13	241 ± 6	12 ± 7	256 ± 12	1.72 ± 0.07	252
Dilepton mass cuts	0.86 ± 0.07	12.2 ± 0.6	5 ± 5	18 ± 5	0.48 ± 0.03	12
Angular cut	0.64 ± 0.06	9.0 ± 0.5	4 ± 4	14 ± 4	0.45 ± 0.03	9
Overlap removal	0.63 ± 0.06	8.7 ± 0.5	4 ± 4	14 ± 4	0.42 ± 0.03	8
Z-enriched ($ee\mu + \mu\mu e$)	9.54 ± 0.29	1180 ± 29	530 ± 90	1730 ± 120	9.25 ± 0.18	1968
Jet multiplicity and b-veto	7.97 ± 0.29	1008 ± 29	420 ± 90	1440 ± 120	6.56 ± 0.14	1490
$E_{\mathrm{T,rel}}^{\mathrm{Miss}}$ cut	4.24 ± 0.19	219 ± 7	12 ± 6	235 ± 12	2.37 ± 0.08	247
Dilepton mass cuts	2.35 ± 0.13	15.6 ± 0.8	2.3 ± 1.8	20.3 ± 2.3	1.17 ± 0.05	24
Angular cut	1.67 ± 0.11	10.8 ± 0.6	0.65 ± 0.22	13.2 ± 0.8	1.11 ± 0.04	16
Overlap removal	1.56 ± 0.11	10.1 ± 0.6	0.50 ± 0.20	12.2 ± 0.7	1.04 ± 0.04	16
Z-depleted	4.10 ± 0.16	6.0 ± 0.4	20 ± 4	30 ± 4	1.98 ± 0.06	38
Jet multiplicity and b-veto	3.61 ± 0.16	4.79 ± 0.33	7 ± 4	15 ± 4	1.66 ± 0.05	16
$E_{\mathrm{T,rel}}^{\mathrm{Miss}}$ cut	2.42 ± 0.12	1.82 ± 0.20	0.8 ± 0.4	5.0 ± 0.6	1.05 ± 0.04	12
Dilepton mass cut	2.40 ± 0.12	1.81 ± 0.20	0.8 ± 0.4	5.0 ± 0.6	1.01 ± 0.04	12
Angular cut	1.54 ± 0.09	0.86 ± 0.14	0.8 ± 0.4	3.2 ± 0.5	0.92 ± 0.04	10
Overlap removal	1.45 ± 0.09	0.68 ± 0.12	0.58 ± 0.35	2.7 ± 0.5	0.88 ± 0.04	9

After the selection on $E_{\mathrm{T,rel}}^{\mathrm{Miss}}$, an excess of events is observed in the *Z-depleted* sample. After all selection cuts, 9 events are observed in data, while 2.7 ± 0.5 background events plus 0.88 ± 0.04 signal events for $m_H = 125$ GeV are expected. The candidate events were carefully scrutinized and no detector effect or any other anomaly which could explain the discrepancy was found. The resulting expected, calculated in the absence of the SM Higgs boson, and observed upper limits at 95% confidence level (C.L.) are presented in Fig. 1. At $m_H = 125$ GeV, the expected and observed limits are 5.2 and 10.0 times the SM cross section respectively. The size of the observed excess is quantified by computing the local probability for a background fluctuation to produce, in the absence of any signal, a number of events at least as large as the observed one (p_0). At $m_H = 125$ GeV, this probability is $p_0 = 1.2\%$, corresponding to a significance of the excess of 2.3σ. The size of the excess is also computed in the background plus the SM Higgs boson signal scenario (local probability p_1). At $m_H = 125$ GeV, the significance of the excess with respect to the background plus SM Higgs boson signal is 1.8σ ($p_1 = 3.3\%$).

To complete the study of the $WH \to WWW^{(*)} \to l\nu l\nu l\nu$ channel, a combination is performed with the results obtained from data collected at a center-of-mass energy of 7 TeV reported in Ref. [5]. In Fig. 2 the expected and observed upper limits at 95% confidence level (C.L.) are presented. At $m_H = 125$ GeV, the expected and observed limits are 4.1 and 7.5 times the SM cross section respectively. The observed significance with respect to the background-only hypothesis is 1.6σ ($p_0 = 4.9\%$), while including the SM Higgs boson signal is 1.1σ ($p_1 = 13\%$).

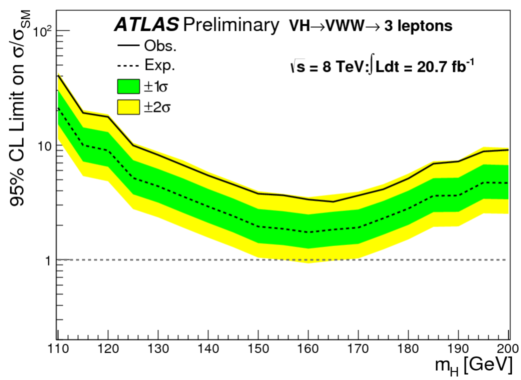

Fig. 1. Upper limits, observed (continuous line) and expected (dashed line), at 95% C.L. on the WH production using 20.7 fb^{-1} at $\sqrt{s} = 8$ TeV in the SM Higgs scenario [4]. For the SM Higgs boson at $m_H = 125$ GeV, the expected and observed limits are respectively 5.2 and 10.0 times the SM cross section.

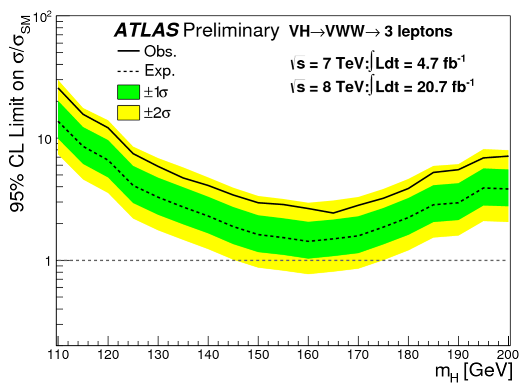

Fig. 2. Upper limits, observed (continuous line) and expected (dashed line), at 95% C.L. on the WH production using data acquired by the ATLAS experiment up to the 2012 end [4]. For the SM Higgs boson at $m_H = 125$ GeV, the expected and observed limits are respectively 4.1 and 7.5 times the SM cross section.

3. 4-lepton analysis

In this section, a study of the production of the Higgs boson in association with Z boson with a fully leptonic final state is presented. Only muons and electrons are considered in the final state. Data were collected in 2012 at $\sqrt{s} = 8$ TeV by the ATLAS experiment. The analysis goal is to study the ZH production focusing on the Higgs boson mass hypothesis of 125 GeV. As in the 3-leptons analysis in order to allow a statistical combination of the results presented here with the 2-lepton analysis, the events in overlap were explicitly removed. This analysis requires the presence of four isolated leptons with total charge equal to zero and high missing transverse momentum. The background processes are classified as in the 3-lepton analysis but here the triboson and diboson categories are dominated by $ZWW^{(*)}$ and $ZZ^{(*)}$ productions respectively. In this analysis, the main source of background is $ZZ^{(*)} \to llll$ with fake missing transverse momentum and is characterized by the fact that, with the exception of $Z \to \tau\tau$ decays, the final state consists of two pairs of the same-flavor leptons. The events are classified according to the multiplicity of SFOS lepton pairs in categories with different contributions from $ZZ^{(*)}$ production. The reconstruction of the $ZH \to ZWW^{(*)} \to lll\nu l\nu$ decay proceeds through the identification of the two lepton candidates from the recoiling Z boson, hereafter called l_2 and l_3, followed by the identification of the lepton candidates from the Higgs boson decay chain, labeled l_0 and l_1.

3.1. 4-lepton analysis selections

The pre-selection requires events containing exactly four isolated leptons with $p_{\mathrm{T}} > 10$ GeV and a total charge 0. Events are accepted if at least one of these leptons matches an object responsible for a single-lepton trigger. The transverse momenta of the leading, sub-leading, 3$^{\mathrm{rd}}$ and 4$^{\mathrm{th}}$ leptons must be respectively above 25 GeV, 20 GeV, 15 GeV and 10 GeV. In order to suppress events without any neutrino in the final state the missing transverse momentum $E_{\mathrm{T}}^{\mathrm{Miss}}$ is required to be above 30 GeV. Events are required to contain at most one jet with $p_{\mathrm{T}} > 25$ GeV, which should not be b-tagged. This selection allows to suppress the $t\bar{t}Z$ background contribution. Following the lepton labeling described above, selections on the invariant masses $m_{l0,l1}$ and $m_{l2,l3}$ are performed. $m_{l2,l3}$ is required to be within 10 GeV from the Z boson mass, while $m_{l0,l1}$ is required to be between 10 GeV and 65 GeV. This selection excludes the Z boson mass region and suppresses the $ZZ^{(*)}$ background in events with two pairs of SFOS leptons. Given the expected angular correlation between the leptons coming from the Higgs boson decay, an upper cut at 2.5 on the absolute difference in azimuthal angle between the two leptons from the Higgs boson candidate in the transverse Higgs boson frame ($\Delta\phi_{01}^{\mathrm{boost}}$) is used to improve the sensitivity of the analysis.

A requirement on the magnitude of the vector sum of the lepton four-momenta, $p_{\mathrm{T}4l} > 30$ GeV, is applied in the 2 SFOS lepton pairs sample to discriminate between the signal and the $ZZ^{(*)}$ background. To remove the overlap with the $H \to ZZ^{(*)} \to llll$ analysis from the 2 SFOS lepton pairs sample, the invariant mass of the four leptons (m_{4l}) is required to be greater than 130 GeV. To allow a combination with the other Higgs boson production mechanisms involving the $H \to WW^{(*)}$ events selected by the 2-lepton search, described in Ref. [3], are removed.

3.2. 4-lepton analysis result

The number of expected events after each of the selections described in previous section is presented in Table II.

TABLE II

Number of expected and observed events at several stages of the cutflow for the different signal regions of the 4-lepton analysis [4].

	ZZ	VVV	Fakes	Total bkg.	$VH(125)$	Data
4 leptons	164 ± 6	1.89 ± 0.08	8.8 ± 5.8	175 ± 10	0.89 ± 0.04	182
$E_{\mathrm{T}}^{\mathrm{Miss}}$ and p_{T}	41.8 ± 1.6	1.65 ± 0.07	7.8 ± 5.3	51.3 ± 5.6	0.71 ± 0.03	55
Jet multiplicity and b-veto	30.8 ± 1.1	1.30 ± 0.06	0.31 ± 0.11	32.5 ± 1.2	0.52 ± 0.02	35
Mass cuts	2.97 ± 0.15	0.22 ± 0.02	0.05 ± 0.03	3.24 ± 0.16	0.41 ± 0.02	2
Angular cut	1.88 ± 0.12	0.20 ± 0.02	0.04 ± 0.02	2.12 ± 0.12	0.39 ± 0.02	2
1 SFOS lepton pair	0.24 ± 0.04	0.08 ± 0.01	0.00 ± 0.01	0.33 ± 0.05	0.19 ± 0.01	2
Overlap removal	0.23 ± 0.04	0.08 ± 0.01	0.00 ± 0.01	0.32 ± 0.05	0.18 ± 0.01	2
2 SFOS lepton pairs	1.64 ± 0.11	0.12 ± 0.01	0.04 ± 0.02	1.79 ± 0.11	0.20 ± 0.01	0
4 leptons system cuts	0.72 ± 0.07	0.11 ± 0.01	0.04 ± 0.02	0.86 ± 0.08	0.18 ± 0.01	0
Overlap removal	0.70 ± 0.07	0.10 ± 0.01	0.04 ± 0.02	0.84 ± 0.08	0.17 ± 0.01	0

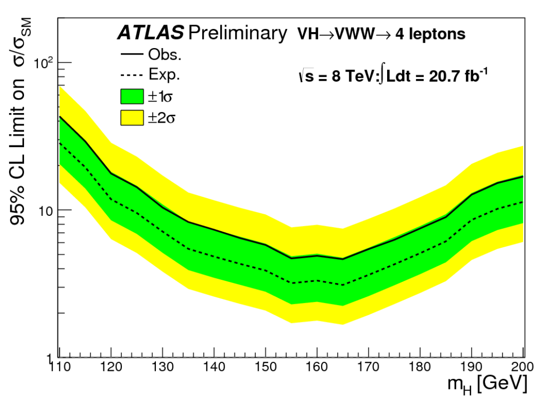

Fig. 3. Upper limits, observed (continuous line) and expected (dashed line), at 95% C.L. on the ZH production using 20.7 fb^{-1} at $\sqrt{s} = 8$ TeV in the SM Higgs scenario [4]. For the SM Higgs boson at $m_H = 125$ GeV, the expected and observed limits are respectively 9.6 and 14.3 times the SM cross section.

The expected, calculated in the absence of the SM Higgs boson, and observed upper limits at 95% C.L. are presented in Fig. 3. At $m_H = 125$ GeV, the expected and observed limits are 9.6 and 14.3 times the SM cross section respectively. At $m_H = 125$ GeV, data are compatible with the background-only hypothesis at the 1.5σ level ($p_0 = 7.2\%$) and with the signal plus background hypothesis at the 1σ level ($p_1 = 17\%$).

4. Combination

The results of the analyses described in the previous sections are combined in a single VH result. In particular, the results from 2011 and 2012 analyses of the WH are combined with the ZH one to derive the expected and observed upper limit at 95% C.L. shown in Fig. 4. The expected and observed limits, at $m_H = 125$ GeV, are 3.6 and 7.2 times the SM cross section respectively. The signal strength and the local probability p_0 and p_1 are derived as well. For $m_H = 125$ GeV, data are compatible with the background-only hypothesis at the 2.0σ level ($p_0 = 2.1\%$) and with the signal plus background hypothesis at the 1.4σ level ($p_1 = 7.9\%$), while the fitted signal strength is $3.7^{+1.9}_{-2.0}$ times the expected SM Higgs boson signal.

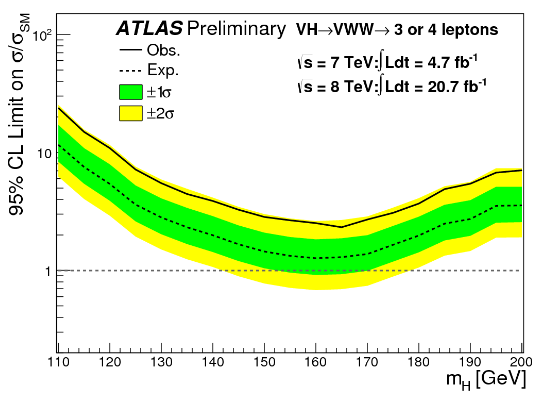

Fig. 4. Upper limits, observed (continuous line) and expected (dashed line), at 95% C.L. on the VH production using the 3-lepton analysis of the 7 TeV and 8 TeV data and the 4-lepton analysis of the 8 TeV [4]. For the SM Higgs boson at $m_H = 125$ GeV, the expected and observed limits are respectively 3.6 and 7.2 times the SM cross section.

The VH analysis results reported in this section are combined with the results of the $H \to WW^{(*)} \to l\nu l\nu$ analysis reported in Ref. [3], which targets mainly the Higgs boson production through the gluon–gluon fusion mechanism and the vector boson fusion process. In Fig. 5 the expected and observed local p_0 for this combination are reported as a function of the Higgs boson mass hypothesis, while in Table III the expected and observed significance for the Higgs boson mass of 125 GeV are presented.

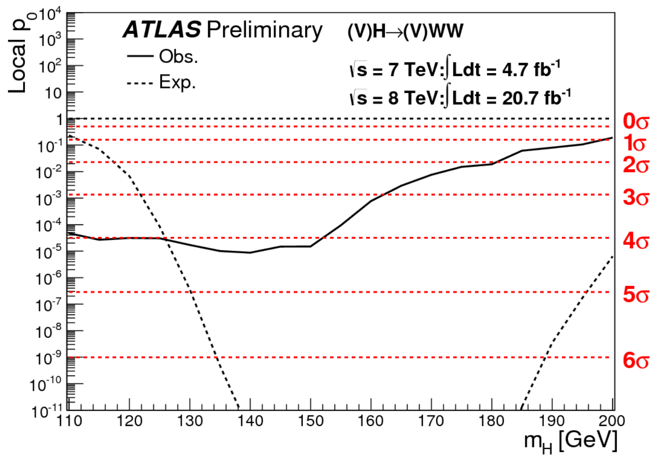

Fig. 5. The observed (continuous line) and expected (dashed line) local p_0 as a function of the hypothesized Higgs boson mass for the combination of VH and $H \to WW^{(*)} \to l\nu l\nu$ analyses [4].

TABLE III

Expected and observed significance for the VH and $H \to WW^{(*)} \to l\nu l\nu$ analyses and their combination, for $m_H = 125$ GeV [4].

Significance (σ)	VH	$H \to WW^{(*)} \to l\nu l\nu$ [3]	Combined
Expected	0.7	3.7	3.8
Observed	2.0	3.8	4.0

5. Conclusion

Final states containing three or four leptons have been used to search for the associated production of the Higgs boson with W or Z boson, with subsequent decay of the Higgs boson to WW and of all three gauge bosons to electrons or muons, using data collected by the ATLAS experiment at the LHC in pp collisions at a center-of-mass energy of 8 TeV. Limits are set on the production cross section divided by the SM Higgs boson expectation in a mass interval 110 GeV $\leq m_H \leq$ 200 GeV. Combining the result with the search performed on data collected by the ATLAS experiment at

$\sqrt{s} = 7$ TeV [5], for the Higgs boson mass $m_H = 125$ GeV the 95% C.L. observed (expected) limit is 7.2 (3.6) times the Standard Model cross section. The expected and observed local p_0 values, for the combination of the VH result with those from $H \to WW^{(*)} \to l\nu l\nu$, are reported as a function of the Higgs boson mass. For the Higgs boson mass of $m_H = 125$ GeV, the observed (expected) p_0 is 4.0σ (3.8σ).

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