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Search for the Standard Model Higgs boson in the $H\left(\to WW^{(*)}\right) \to l\nu l\nu, l\nu qq$ decay modes with the ATLAS detector

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A Higgs boson search in the $H(\to WW^{(*)}) \to l\nu l\nu, lqq$ decay mode has been performed using proton-proton collisions produced by the LHC hadron collider and recorded by the ATLAS experiment. The search in the final state with two leptons and two neutrinos covers a broad mass range from 110 - 600 GeV. Upper limits are derived on the cross section times branching ratio of a Standard Model Higgs boson.The semi-leptonic final state with a lepton, neutrino and two or more jets provides additional sensitivity to the fully-leptonic decay mode in the high mass region from 300 to 600 GeV. First results on the search for associated production of a Higgs boson via the $WH(\to WW^{(*)}) \to l\nu l\nu l\nu$ final state are presented.

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1. Introduction

The Higgs boson was the only elementary particle in the Standard Model (SM) of particle physics that had not yet been observed. It is intimately related to the electroweak symmetry breaking mechanism which in the SM gives mass to all other massive elementary particles, and in particular to the W and Z vector bosons.

The Higgs boson discovery has been claimed by both the ATLAS[1] and CMS collaboration [2],[3] with combined significances of $\sim 6\sigma$ and $\sim 5\sigma$ respectively.

Exclusion limits in the allowed mass range from the electroweak precision tests, $m_H < 200$ GeV, were published by the ATLAS experiment specifically in the $H(\to WW^{(*)}) \to l\nu l\nu$ channel excluding a Higgs boson in the range $145 < m_H < 206$ GeV at 95% C.L. [4] using an integrated luminosity of 2.05 fb^{-1} at $\sqrt{s} = 7$ TeV.

In this paper we report the update of this analysis using the full 2011 dataset [5] corresponding to 4.7 fb^{-1} of integrated luminosity in the $H(\to WW^{(*)}) \to l\nu l\nu$ channel that has been produced using a cut based technique. Preliminary results obtained using a Boosted Decision Tree (BDT) [6] are also presented for the $l\nu l\nu$ channel.

Moreover we summarise the results for the search in the final state $l\nu jj$ [7] and the associated production channel WH[8].

2. The $H(\to WW^{(*)}) \to l\nu l\nu$ analysis

The data used for the $H(\to WW^{(*)}) \to l\nu l\nu$ analysis were collected in 2011 using the ATLAS detector. In this analysis the signal contributions that are considered include the dominant gluon fusion production process ($gg \to H$, denoted as ggF), the vector-boson fusion production process ($qq' \to qq'H$, denoted as VBF) and the Higgs-strahlung processes ($qq' \to WH, qq' \to ZH$ denoted as WH/ZH). For the decay of the Higgs boson only the $H(\to WW^{(*)}) \to \ell\nu\ell\nu$ mode is considered with final states featuring two charged leptons ($\ell = e, \mu$ and including small contributions from leptonic τ decays).

The Monte Carlo (MC) generators used to model signal and background processes are *Powheg + Pythia6* for the signal, *MC@NLO+Herwig* for the dominant non resonant WW background and for the $t\bar{t}$ background, and *Alpgen+Herwig* for the modelling of the Z/γ^* background. Other, less important, backgrounds are modelled with the *Sherpa* and *Madgraph* + *Pythia*6 generators.

$H(\to WW^{(*)}) \to \ell\nu\ell\nu$ candidates (with $\ell = e, \mu$) are pre-selected by requiring exactly two oppositely isolated charged leptons with p_{T} thresholds of 25 GeV and 15 GeV for the leading and sub-leading leptons respectively.

The Drell-Yan process is suppressed in the ee and $\mu\mu$ channels by requiring the dilepton invariant mass to be greater than 12 GeV, and to differ from the Z-boson mass m_Z by at least 15 GeV. For the $e\mu$ channel, the dilepton invariant mass is required to be greater than 10 GeV.

Drell-Yan events and multijet production via QCD processes are suppressed by requiring large $E_{\mathrm{T}}^{\mathrm{miss}}$. The $E_{\mathrm{T}}^{\mathrm{miss}}$ is the magnitude of $p_{\mathrm{T}}^{\mathrm{miss}}$, the negative vector sum of the reconstructed objects' transverse momenta.

The quantity $E_{\mathrm{T,rel}}^{\mathrm{miss}}$ used in this analysis is defined as: $E_{\mathrm{T,rel}}^{\mathrm{miss}} = E_{\mathrm{T}}^{\mathrm{miss}} \sin\Delta\phi_{\mathrm{min}}$, with $\Delta\phi_{\mathrm{min}} \equiv \min(\Delta\phi, \frac{\pi}{2})$. Here, $\Delta\phi$ is the angle between $p_{\mathrm{T}}^{\mathrm{miss}}$ and the transverse momentum of the nearest lepton or jet with $p_{\mathrm{T}} > 25$ GeV. For the ee and $\mu\mu$ channels the multijet and Drell-Yan events are suppressed by requiring $E_{\mathrm{T,rel}}^{\mathrm{miss}} > 45$ GeV. In the $e\mu$ channel Drell-Yan events originate predominantly from $\tau\tau$ production, where the small leptonic τ decay branching fractions lead to a much smaller background. In this channel the requirement is relaxed to $E_{\mathrm{T,rel}}^{\mathrm{miss}} > 25$ GeV.

The data are subdivided into 0-jet, 1-jet and 2-jet channels according to the jet counting defined above with the 2-jet channel also including higher jet multiplicities. In addition, slightly different requirements are used for $m_H < 200$ GeV, 200 GeV $\leq m_H \leq 300$ GeV, and 300 GeV $< m_H < 600$ GeV; in the following these are referred to as low m_H, intermediate m_H, and high m_H selections, respectively.

Due to spin correlations in the $WW^{(*)}$ system arising from the spin-0 nature of the Higgs boson, the charged leptons tend to emerge from the interaction point in the same direction. In the low m_H selection this kinematic feature is exploited for all jet multiplicities by requiring $\Delta\phi_{\ell\ell}$ be less than 1.8 radians, and that the dilepton invariant mass, $m_{\ell\ell}$, be less than 50 GeV for the 0-jet and 1-jet channels. The region $m_{\ell\ell} > 80$ GeV is used to normalise the WW background to data, reducing the impact of both theoretical and experimental systematics. For the 2-jet channel, the $m_{\ell\ell}$ upper bound is increased to 80 GeV. For $m_H \geq 200$ GeV, the leptons tend to have higher p_{T} and larger angular separation. Therefore the $\Delta\phi_{\ell\ell}$ cut is omitted and the $m_{\ell\ell}$ upper bound is increased to 150 GeV. For $m_H > 300$ GeV the $m_{\ell\ell} < 150$ GeV criterion is also omitted. In the 0-jet channel, the magnitude $p_{\mathrm{T}}^{\ell\ell}$ of the transverse momentum of the dilepton system is required to be greater than 30 GeV for the $e\mu$ channel and greater than 45 GeV for the ee and $\mu\mu$ channels.

In the 1-jet channel, backgrounds from top quark decays are suppressed by rejecting events containing a b-tagged jet. The $\tau\tau$ invariant mass, $m_{\tau\tau}$, is computed under the assumption that the reconstructed leptons are τ lepton decay products, that the neutrinos produced in the τ decays are collinear with the leptons, and that they are the only source of $E_{\mathrm{T}}^{\mathrm{miss}}$.

The 2-jet selection follows the 1-jet selection described above (with the $p_{\mathrm{T}}^{\mathrm{tot}}$ definition modified to include all selected jets). In addition, the following jet-related cuts are applied: the two highest-p_{T} jets in the event, the "tag" jets, are required to lie in opposite pseudorapidity hemispheres ($\eta_{\mathrm{j1}} \times \eta_{\mathrm{j2}} < 0$), with no additional jet within $|\eta| < 3.2$; the tag jets must be separated in pseudorapidity by a distance $|\Delta\eta_{\mathrm{jj}}|$ of at least 3.8 units; finally, the invariant mass of the two tag jets, m_{jj}, must be at least 500 GeV.

A transverse mass variable, m_{T}, is used in this analysis to test for the presence of a signal. This variable is defined as:

$$m_{\mathrm{T}} = \sqrt{(E_{\mathrm{T}}^{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - |\mathbf{p}_{\mathrm{T}}^{\ell\ell} + \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}|^2},$$

where $E_{\mathrm{T}}^{\ell\ell} = \sqrt{|\mathbf{p}_{\mathrm{T}}^{\ell\ell}|^2 + m_{\ell\ell}^2}$. Figure [1] (left) shows the distributions of the transverse mass after all the low m_H selection criteria in the 0-jet and 1-jet analyses, for all lepton flavours combined.

The m_T shape is fitted in the 0 and 1 jet analyses while a single bin $0 < m_T < 200$ GeV is kept in the 2 jet analysis. The combined exclusion limits, observed and expected, are shown in Fig. [1] (right). A Higgs boson is excluded in the $WW^{(*)}$ dilepton channel in the range $133 < m_H < 261$ GeV at 95% C.L while the expected exclusion is in the range $127 < m_H < 233$ GeV. The region between 127 GeV and 133 GeV cannot be excluded due to a mild excess of events at low mass with a significance of 1 σ, where the observed excess became more pronunced in the 2012 data reaching a total significance of 2.8 σ [2].

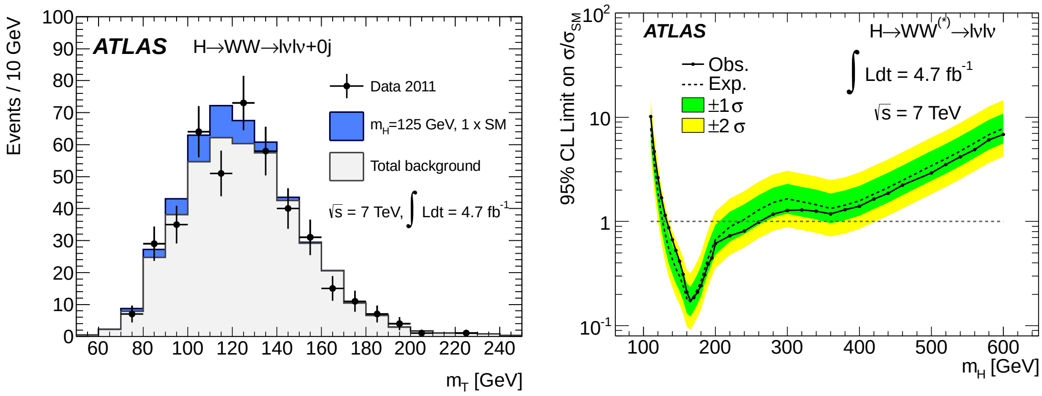

Figure 1: (left) Transverse mass, m_T, distribution in the 0-jet for events satisfying all criteria for the low m_H selection. The lepton flavours are combined. The expected signal for a SM Higgs boson with $m_H = 125$ GeV is superimposed; (right) CLs limit on the σ/σ_{SM} from the cut based analysis. This figure is taken from [5].

The present analysis has been refined using a Boosted Decision Tree, a multivariate technique. The BDT analysis uses the same selection criteria and background description as the cut based analysis but instead of defining cuts on the variables p_T^{ll}, m_{ll}, $\Delta\phi_{ll}$ and m_T uses those as inputs to a BDT discriminant. The BDT is trained against the signal and background hypotheses and a normalised output between 0 and 1 is obtained. The BDT output for 1 jet is shown in Fig. 2 left as an example, and in the same figure on the right we show the CLs limit obtained with the BDT output in the region $110 < m_H < 150$ GeV. The observed exclusion limit is $130 < m_H < 281$ GeV at 95% C.L while we expect an exclusion in the range $127 < m_H < 255$ GeV.

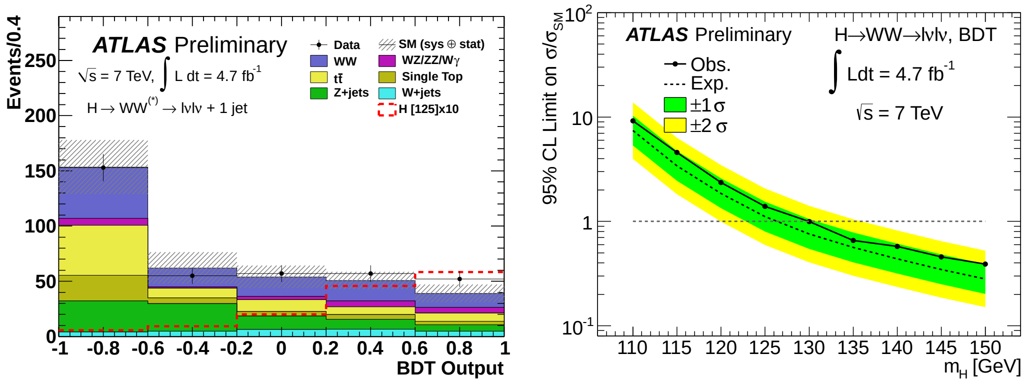

Figure 2: (left) BDT output distribution for the 1 jet events. The signal is superimposed with a scale factor of 10 for better visualisation; (right) CLs limit from the BDT analysis in the region $110 < m_H < 150$ GeV. This figure is taken from [6].

3. The $H(\to WW^{(*)}) \to l\nu jj$ analysis

The $l\nu jj$ final state is an interesting channel that profits from the large $Br(W \to qq)$ and from the presence of just one neutrino. Using the momentum conservation in the transverse plane, the measurement of the E_T^{miss} of the system and the mass of the W is possible to reconstruct the invariant mass of the $l\nu jj$ system and therefore of the Higgs boson. The main background of this channel is the production of a W in association with jets, this is rejected through an high missing E_T cut, $E_T^{miss} > 40$ GeV and the requirement to have at least two jets that have momenta larger than 60 GeV and 40 GeV and form an invariant mass close to the W boson mass: 71 GeV $< m_{jj} <$ 91 GeV. Furthermore an isolated lepton with $p_T > 40$ GeV is required and no additional lepton with $p_T > 20$ GeV.

The signal is characterized by the presence of a peak in the $m(l\nu jj)$ distribution. The background yield is determined by fitting the observed $m(l\nu jj)$ distribution with the function: $f(x) = [1/(1+|a(x-m)^b)] \times exp[-c(x-200)]$ where x is $m(l\nu jj)$ and a, b, c and m are free parameters. The signal is searched in 3 jet bins defined as the number of extra jets respect to the number of jets from the boson decay: 0, 1, 2, where the 2 jet bin is optimised specifically for the VBF process. The search is performed in the range $300 < m_H < 600$ GeV. The data are compatible with the background only hypothesis and the CLs limit is shown in Fig. [3] (left). In the same figure we show the background subtracted data together with two signal hypotheses.

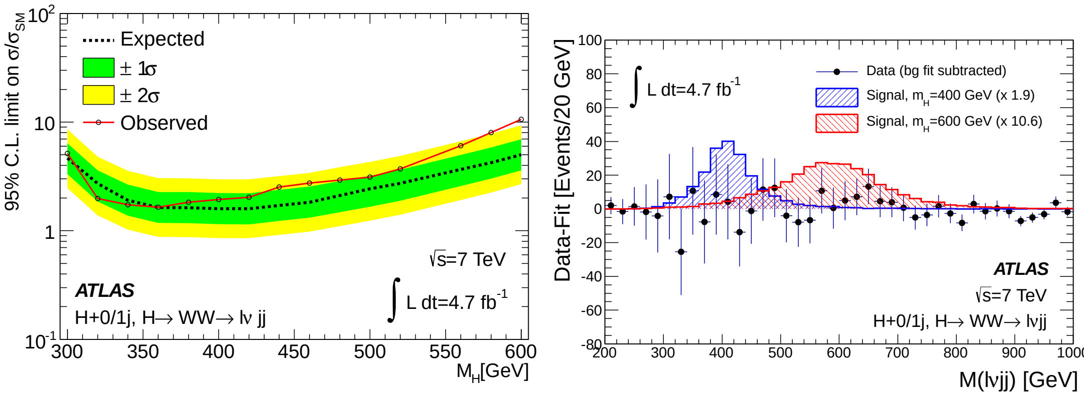

Figure 3: (left) CLs limit for the $H(\to WW^{(*)}) \to l\nu jj$ analysis; (right) data after background subtraction, where the expected contributions of a signal at $m_H = 400$ GeV and $m_H = 600$ GeV are shown. This figure is taken from [7].

4. The WH analysis

The Higgs-strahlung process is of particuar interest for the study of the Higgs properties. Its rate is proportional to the fouth power of the $H \to WW^{(*)}$ coupling. The signal is defined by the decay chain $WH(\to WW^{(*)}) \to l\nu l\nu l\nu$, therefore a 3 lepton final state is required. The sample is divided in 2 categories, one Z enriched category and one Z depleted category. Events belonging to the Z enriched category have events with two leptons of same flavour and opposite charge while the Z depleted category does not contain such events. This category has a large contamination from non resonant WZ events. A cut on $E_{T,rel}^{miss} > 40$ GeV and a dilepton mass outside a Z window of 25 GeV is imposed in the Z enriched category, while the $E_{T,rel}^{miss}$ cut is relaxed down to 25 GeV in the Z depleted category. In the Z enriched category we expect a total number of background events of 3.7 events and 0.39 signal events, while in the Z depleted category the total background is 0.25 events and the total expected signal is 0.22 events. We observe 3.7 events in the Z enriched category and

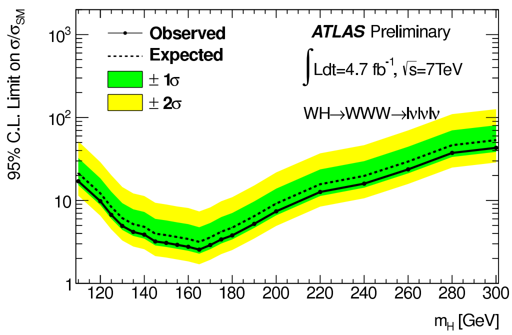

Figure 4: (CLs limit for the $WH(\rightarrow WW^{(*)}) \rightarrow l\nu l\nu l\nu$ analysis. This figure is taken from [8].

0 events in the Z depleted one. The obtained exclusion limit is shown in Fig. 4. The most stringent limit is 2.7 σ_{SM} at $m_H = 165$ GeV.

5. Conclusions

An overview of the ATLAS analysis in the $H \rightarrow WW^{(*)}$ channel has been presented using 2011 data. The most sensitive channel, $H(\rightarrow WW^{(*)}) \rightarrow l\nu l\nu$ excludes a Higgs boson in the range 130 $< m_H <$ 183 GeV at 95% C.L. For lower m_H values an excess with a significance of 1 σ has been observed. This excess has been confirmed in the 2012 analysis with much stronger significance and has been published in [2] shortly after the present conference.

References

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