IL NUOVO CIMENTO Vol. 37 C, N. 1 Gennaio-Febbraio 2014
DOI 10.1393/ncc/i2014-11695-4

Colloquia: IFAE 2013

Higgs results in the $WW^{(*)} \to l\nu l\nu$ decay channel at ATLAS

M. Testa on behalf of the ATLAS Collaboration
INFN, Laboratori Nazionali di Frascati - Frascati (RM), Italy

ricevuto l'1 Ottobre 2013

Summary. — In this paper the evidence of a Higgs-like boson candidate in the $H \to WW \to l\nu l\nu$ channel, observed by the ATLAS experiment at the LHC, is presented. The data sample used corresponds to an integrated luminosity of $20.7\,\text{fb}^{-1}$ at a center-of-mass energy of 8 TeV and $4.6\,\text{fb}^{-1}$ at 7 TeV. The analyses focuses on the search of the Standard Model Higgs Boson with $m_H = 125\,\text{GeV}$. The significance of the observed excess of events over the expected number of background events is 3.8; the expected value is 3.7. The ratio between the observed and expected numbers of events is consistent with unity, $\mu = 1.0 \pm 0.31$.

PACS 14.80.Bn – Standard-model Higgs bosons.

1. – Introduction

In the summer of 2012, the ATLAS and CMS experiment discovered a Higgs-like boson with a mass of approximately $m_H = 126\,\text{GeV}$ [1, 2]. Recently the evidence of the Standard Model (SM) Higgs-like boson in the $H \to WW^{(*)} \to l\nu l\nu$ channel has been presented by the ATLAS collaboration using the complete data sample of 2012 and 2011 taken at $\sqrt{s} = 8$ and 7 TeV respectively. This channel provides fundamental inputs for the overall production rate and the couplings to weak boson.

2. – Data sample

The data sample used for this analysis was collected using the ATLAS detector [3]. It corresponds to an integrated luminosity of $20.7\,\text{fb}^{-1}$ at a center-of-mass energy of 8 TeV and $4.6\,\text{fb}^{-1}$ at 7 TeV. Data were triggered requiring at least a muon or an electron with $p_T > 24\,\text{GeV}$. In this analysis, the signal contributions, used in the Monte Carlo (MC) simulation, include the dominant gluon-gluon fusion production process ($gg \to H$, denoted as ggF), the vector-boson fusion process ($qq' \to qq'H$, denoted as VBF) and the Higgs-strahlung process ($qq' \to WH, ZH$, denoted as VH). More information on the MC samples used for the signal and the background processes can be found in [4].

3. – Objects definition and event selection

The experimental signature of $H \to WW^{(*)} \to l\nu l\nu$ events is characterized by two high p_T leptons with same flavour (SF), ee and $\mu\mu$, or opposite flavour (OF), eμ and μe, large missing transverse energy ($\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}$), due to the presence of neutrinos in the final states, and 0,1 or ≥ 2 jets (N_{jets}).

Electron candidate are selected by applying tight identification criteria using a combination of tracking and calorimeter information and are required to be in the range of $|\eta| < 2.47$ excluding $1.37 < |\eta| < 1.52$. Muon candidates are identified by matching track reconstructed in the inner detector and in the muon spectrometer and are required to be in the range $|\eta| < 2.5$. At least on the leptons candidate must match a trigger object. Jets are reconstructed using the anti-k_t algorithm with distance parameter $R = 0.4$ and are required to have $p_T > 25\,\mathrm{GeV}$ if $|\eta| < 2.4$ and $p_T > 30\,\mathrm{GeV}$ if $2.4 < |\eta| < 4.5$. $\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}$ is computed from the negative vectorial sum of the muon, electrons,photons, jets, and clusters of calorimeter cells not associated to these objects. For events in the $N_{jet} \leq 1$ modes, a requirement is made on $E_{\mathrm{T}}^{\mathrm{miss}}{}_{rel}$, which is defined as: $E_{\mathrm{T}}^{\mathrm{miss}}{}_{rel} = E_{\mathrm{T}}^{\mathrm{miss}} \times sin(\Delta\phi_{min})$ where $\phi_{min} = \min(\Delta\phi, \pi/2)$ and $\Delta\phi$ is the azimuthal angular difference between the $\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}$ vector and the nearest candidate leptons or jet. Due to large amount of Drell-Yan (DY) background with fake $\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}$ in events with many pile-up interactions, additional variables are used to further reduce this background: $\boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}}$, a track-based measurement of the missing transverse momentum, reconstructed selecting tracks from the primary interaction and f_{recoil}, the soft hadronic recoil opposite to the di-lepton system and any accompanying jet for $N_{jet} \leq 1$. Detailed information on the objects definition and on the events selection can be found in [4].

Since the rate and background composition depend on the jet multiplicity, the analysis has been splitted in bins of in N_{jet}.

For $N_{jet} \leq 1$ the signal originates from the ggF process and WW events dominate the background composition. For $N_{jet} \geq 2$ the signal comes mostly from the VBF process and $t\bar{t}$ events dominate the background. For all jet multiplicities, topological cuts are applied. Due to spin correlation in the $H \to WW^{(*)}$ decay and the $V - A$ structure of the W decay, the two leptons emerge in the same direction. The leptons invariant mass is therefore required to be small, $m_{ll} < 50\,\mathrm{GeV}$ for $N_{jet} \leq 1$ and $m_{ll} < 60\,\mathrm{GeV}$ for $N_{jet} \geq 2$ and their azimuthal separation is required to be small, $|\Delta\phi_{ll}| < 1.8$. In the $N_{jet} = 0$ analysis for the OF channel, a cut on $E_{\mathrm{T}}^{\mathrm{miss}}{}_{rel} > 25\,\mathrm{GeV}$ is applied. For the SF channel the selection is tighter, because of the large Z/γ^* background: $E_{\mathrm{T}}^{\mathrm{miss}}{}_{rel} > 25\,\mathrm{GeV}$ and $p_{T,rel}^{\mathrm{miss}} > 45\,\mathrm{GeV}$ and the hadronic recoil is required to be small, $f_{recoil} < 0.05$. The transverse momentum of the di-leptons system is required to be large, $p_T^{ll} > 30\,\mathrm{GeV}$. In the $N_{jet} = 1$ analysis, the $E_{\mathrm{T}}^{\mathrm{miss}}{}_{rel}$ and $p_{T,rel}^{\mathrm{miss}}$ requirements are the same as in $N_{jet} = 0$, but the requirement on hadronic recoil is looser, $f_{recoil} < 0.2$. The top background is suppressed by rejecting events with a heavy-flavour jet identified with a multi-variate b-tagging algorithm. The $Z/\gamma^* \to \tau\tau$ background in OF channel is reduced using the invariant mass calculated for the τ hypothesis, $|m_{\tau\tau} - m_Z| > 25\,\mathrm{GeV}$. In the $N_{jet} \geq 2$ analysis, the VBF-specific kinematics of the two highest-p_T jets in the event (tag jets) are used. Their rapidity gap is required to be large, $\Delta y_{jj} > 2.8$ and their invariant mass is required to be high, $m_{jj} > 500\,\mathrm{GeV}$. To reduce ggF contributions, events with a jet with $p_T > 20\,\mathrm{GeV}$ inside the rapidity gap are vetoed. $t\bar{t}$ background is suppressed by requiring a small total transverse moment, $p_T^{tot} < 45\,\mathrm{GeV}$, where $\boldsymbol{p}_{\mathrm{T}}^{\mathrm{tot}} = \boldsymbol{p}_{\mathrm{T}}^{\mathrm{ll}} + \boldsymbol{p}_{\mathrm{T}}^{\mathrm{jj}} + \boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}$, where $\boldsymbol{p}_{\mathrm{T}}^{\mathrm{tot}}$ is the vectorial sum of the transverse momenta of the tag jets.

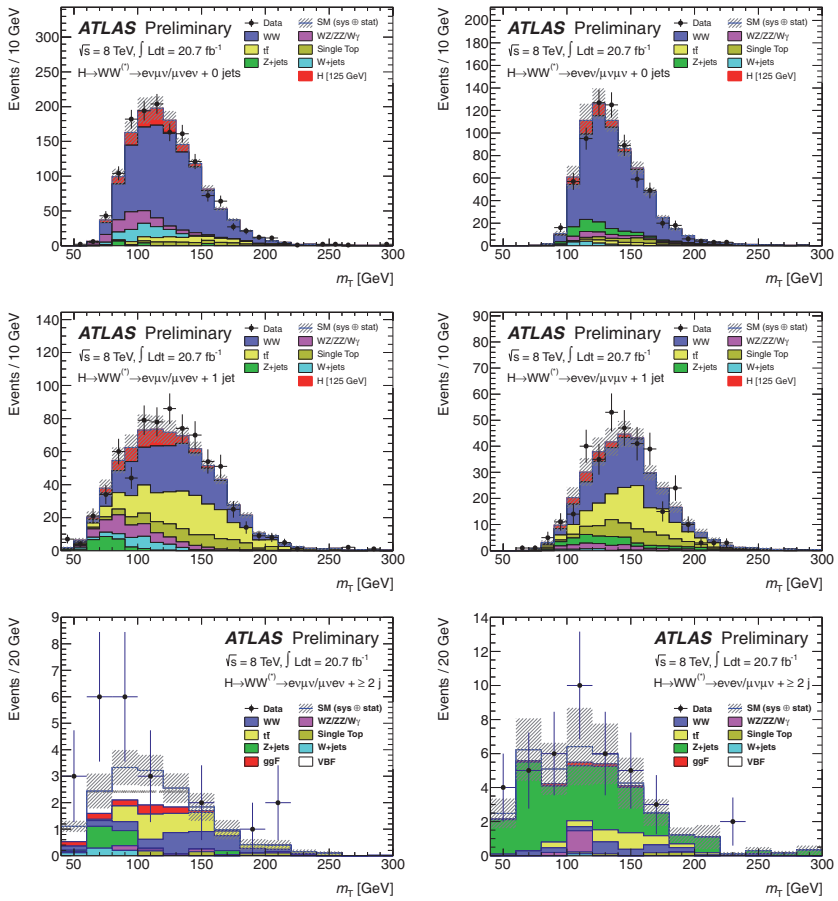

Fig. 1. – Distributions for the transverse mass, m_T, for 8 TeV data. The plots are shown for the $e\mu + \mu e$ (left) and $ee + \mu\mu$ (right) channels in the $N_{jet} = 0$ (top), $N_{jet} = 1$ (middle), $N_{jet} \geq 2$ (bottom) modes. For the $N_{jet} \geq 2$ mode, the signal is plotted separately for ggF and VBF production processes.

4. – Background estimation

Background yields are estimated in control region using correction from the MC simulation. The Z/γ^* yield is estimated from data using a combination of $\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}$, $\boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}}$ and f_{recoil} with uncertainties of 60%, 80% and 15% in the $N_{jet} = 0, 1, \geq 2$ analyses, respectively. The top background ($t\bar{t}$ + single top process) is evaluated in a data control region, defined by reversing the b-jet veto and removing the requirements on $\Delta\Phi_{ll}$ and m_{ll}. The corresponding uncertainties are 28%, 80% and 39% in the $N_{jet} = 1, \geq 2$ analyses, respectively. The WW continuum background has the same final state of the signal, but different lepton spin correlation. Its yield is evaluated in a control region defined by removing the $\Delta\Phi_{ll}$ cut and requiring $50 < m_{ll} < 100\,\mathrm{GeV}$ for $N_{jet} = 0$ and $m_{ll} > 80$ for $N_{jet} = 1$. In the $N_{jet} = 2$ analysis, the WW background is evaluated using only MC simulation. The corresponding uncertainty are 7.4%, 37% and 37% in the $N_{jet} = 0, 1, \geq 2$ analyses, respectively.

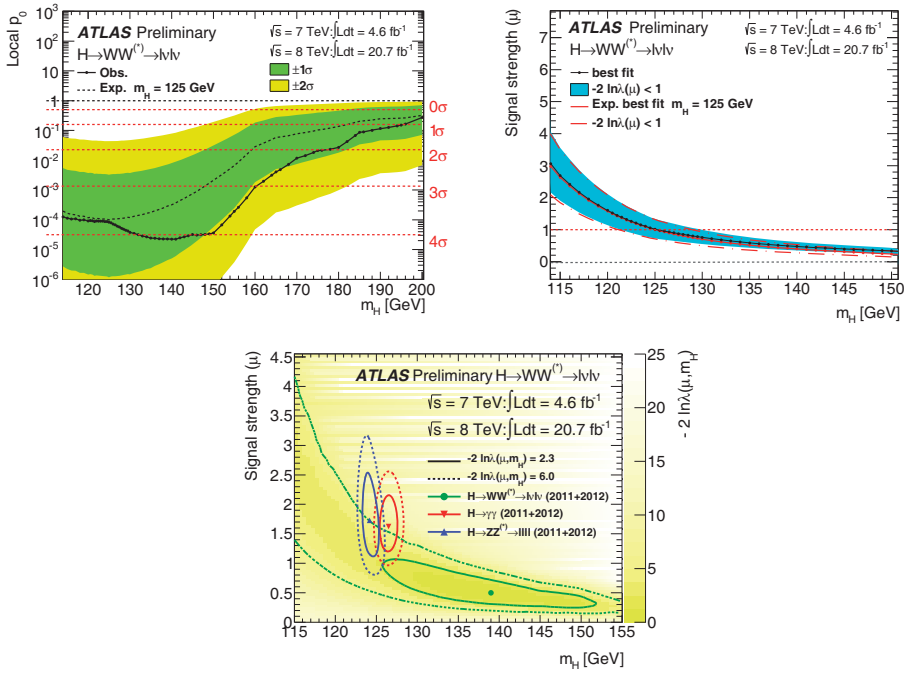

Fig. 2. – Top Left: Results for probability for the background-only scenarios a function of m_H. Smaller green bands represent the $\pm 1\sigma$ uncertainties on the expected value, and the larger yellow band represent $\pm 2\sigma$ uncertainties. Top Right: μ value for fitted results (solid black line with shaded cyan band) and for expected result (solid red line with dashed band). Bottom: $\mu - m_H$ likelihood contour:68% and 95% contour are drawn.

5. – Signal extraction and results

After all cuts described in sect. **3**, the $e\mu + \mu e$ sample is further splitted in two signal regions at $0 < m_{ll} < 30$ and $30 < m_{ll} < 50$, because of the different background amount and composition. A fit to the transverse mass, m_T, distribution is then used to extract the signal yield. m_T is defined as $m_T = ((E_T^{ll} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - |\boldsymbol{p}_{\mathrm{T}}^{\mathrm{ll}} + \mathbf{E}_{\mathrm{T}}^{\mathrm{miss}}|^2)^{1/2}$ with $E_T^{ll} = (|\boldsymbol{p}_{\mathrm{T}}^{\mathrm{ll}}|^2 + m_{ll}^2)^{1/2}$. Figures 1 show the expected signal and the backgrounds for the different N_{jet} analyses and decay channels. The expected and observed results are given combining the jet multiplicity. The expected significance of the signal with $m_H = 125\,\mathrm{GeV}$ is 3.7 s.d. ($p_0 = 1 \times 10^{-4}$). The corresponding observed significance is 3.8 s.d. ($p_0 = 8 \times 10^{-5}$) (fig. 2a). The excess of events is quantified for a signal at $m_H = 125\,\mathrm{GeV}$ by the ratio between the observed and expected numbers of signal events $\mu_{obs} = 1.01 \pm 0.21(stat.) \pm 0.19(theo.\ syst.) \pm 0.12(expt.\ syst.) \pm 0.04(lumi) = 1.01 \pm 0.31$. The dominant systematic uncertainties on μ_{obs} are the theoretical uncertainties on the WW background normalization and on the normalization of the signal yield. The experimental uncertainties on μ_{obs} are dominated by the b-tagging efficiency and the jet energy scale and resolution. Figure 2b shows that the observed μ *vs.* m_H is consistent with the expected distribution in the presence of a signal. Figure 2c shows a scan of the likelihood in the $\mu - m_H$ plane where the $H \to WW^{(*)} \to l\nu l\nu$ result is compared to that of $H \to ZZ^{(*)} \to 4l$ and $H \to \gamma\gamma$.

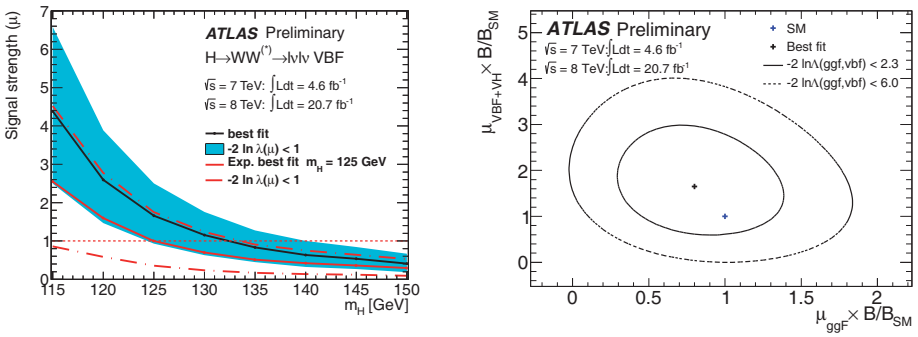

Fig. 3. – Left: VBF signal strenght parameter μ. The observed (solid black line with shaded cyan band) and the expected result (solid red line with dashed band) are shown. Right: Likelihood contours and best-fit value for μ_{ggF} and μ_{VBF}. 68% and 95% contour are shown.

The measured value of the product of the cross section and the $WW^{(*)}$ branching ratio for a signal at $m_H = 125\,\text{GeV}$ at 8 TeV is $6.0 \pm 1.6\,\text{pb}$, while the expected value is $4.8 \pm 0.7\,\text{pb}$. The results are consistent with the prediction for the Standard Model Higgs boson decaying to a pair of W.

Statistical test of a VBF signal are performed by considering the ggF signal as part of the background, and the signal strenght associated with the VBF process, μ_{VBF}, as the parameter of interest. The expected VBF signal significance at $m_H = 125\,\text{GeV}$ is 1.6 s.d. ($p_0 = 0.05$), and the corresponding observed significance is 2.5 s.d. ($p_0 = 0.07$). A 2D simultaneous fit is performed to measure $\mu_{obs,VBF}$ and $\mu_{obs,ggF}$ The best-fit measured single strenght for VBF process at $m_H = 125\,\text{GeV}$ is: $\mu_{obs,VBF} = 1.66 \pm 0.67(stat.) \pm 0.42(syst.) = 1.66 \pm 0.79$ and for ggF process: $\mu_{obs,ggF} = 0.82 \pm 0.24(stat.) \pm 0.28(syst.) = 0.82 \pm 0.36$. Figure 3a shows μ_{VBF} *vs.* m_H. A two-dimensional likelihood scan of the signal strenght for the ggF and VBF production modes are shown in fig. 3b. The results are consistent with the expected SM values of unity.

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