Measurement of Properties of the Higgs Boson in Bosonic Decay Channels using the ATLAS Detector

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The paper reports the properties of the Higgs boson measured in bosonic decay channels ($H \to ZZ^* \to 4\ell$, $H \to \gamma\gamma$, $H \to WW^* \to \ell\ell\nu\nu$ and $H \to Z\gamma \to \ell\ell\gamma$) with 25 fb^{-1} of pp collision data from the LHC run-1 collected by the ATLAS detector. An improved mass measurement, as well as new fiducial and differential cross sections measurements are discussed.

1 Introduction

In the discovery of the Higgs boson, announced by ATLAS [1] and CMS [2] in July 2012, the analyses searching for bosonic decay channels played a crucial role among all channels accessible at the LHC. Since then, using two and a half times more data than was available for the discovery [3], more precise measurements of the properties of this particle have been achieved. Once again the $H \to ZZ^* \to 4\ell$, $H \to \gamma\gamma$ and $H \to WW^* \to \ell\ell\nu\nu$ decay modes have proven to be fundamental in testing the agreement between the observed results and the Standard Model (SM) predictions. Thanks to several refinements achieved in both the $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$ analyses, an improved measurement of the mass of the Higgs boson was recently published. The production modes and therefore the Higgs couplings were tested, and found to be in agreement with theory predictions. In addition, no significant deviations were found following new fiducial and differential cross section measurements, performed in both the $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$ decay channels. Furthermore, an indirect measurement of the Higgs width, Γ_H, was made exploiting the $H \to ZZ^*$ off-peak background interference effects. Finally, a combined measurement of the spin-CP properties of the boson is available. In the following sections the results obtained using approximately 25 fb^{-1} of pp collision data collected at 7 TeV and 8 TeV in 2011 and 2012 are reported.
While in the $H \to Z\gamma \to \ell\ell\gamma$ final state no signal has yet been observed, this channel will be particularly interesting in the coming years due to its sensitivity to the presence of new physics beyond the SM. The last section of this paper describes the analysis and the latest available results.

2 $H \to ZZ^* \to 4\ell$

The $H \to ZZ^* \to 4\ell$ channel provides good sensitivity to the measurement of the Higgs properties due to its high signal-to-background ratio (s/b), which is about two, and its excellent mass resolution varying from 1.6 GeV to 2 GeV depending on the final state.

The analysis searches for two pairs of same-flavor, oppositely charged electrons and muons. Only isolated leptons arising from the same vertex are considered, and they are required to fulfill kinematic cuts and identification quality criteria. In particular, the 2012 data were analysed using a more efficient electron reconstruction algorithm, and an improved likelihood-based electron identification that increased the background rejection by a factor of 2.

Photons originating from final-state radiation (FSR) are searched for and recovered. A kinematic fit is then used to constrain the mass of the leading lepton pair (including FSR photons) to the Z pole mass within the experimental resolution.

The reducible *Z+jets* and $t\bar{t}$ backgrounds are estimated using data-driven methods, while the main ZZ^* background is estimated from simulation and normalized to next-to-leading order calculations. A new boosted decision tree (BDT) discriminant is applied to suppress the ZZ^* contribution, which uses the transverse momentum and pseudorapidity of the four lepton system, and a matrix element kinematic discriminant.

An improved electromagnetic energy calibration and a reduced uncertainty on the muon momentum scale have resulted in a decrease of the systematic uncertainty on the Higgs boson mass. This is measured with a two-dimensional fit to the four lepton invariant mass $\mathrm{m}_{4\ell}$ and the ZZ^* BDT output. The new procedure provides approximately 8% extra sensitivity on the mass with respect to the past, when a simple $m_{4\ell}$ fit was used. The measured Higgs boson mass in the $H \to ZZ^* \to 4\ell$ the decay channel is: $m_H = 124.51 \pm 0.52(\mathrm{stat}) \pm 0.06(\mathrm{syst})$ GeV [4].

By categorising the events according to the characteristics of the different production modes, we can further explore the coupling structure of the Higgs and measure possible deviations from the SM expectations. Four categories are considered: VBF-like, hadronic VH-like, leptonic VH-like and ggF-like. New multivariate techniques are used in the VBF category and in the recently introduced hadronic VH, both characterised by two jets in the final state. An additional lepton is required for the leptonic VH, while the ggF category includes all events discarded by the others. The ratio between the observed and expected signal events, referred to as the signal strength, is extracted at the combined $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ mass value, which will be presented in the following section. For production in gluon fusion or in association with $t\bar{t}$ or $b\bar{b}$ pairs the signal strength is found to be $1.7^{+0.5}_{-0.4}$, while for vector boson fusion combined with *WH/ZH* associated production it is $0.3^{+1.6}_{-0.9}$ [5].

The fiducial and differential cross sections of the Higgs boson production have been recently measured in the $H \to ZZ^* \to 4\ell$ decay channel. The extraction of the signal yield for the measurement of the fiducial cross section is performed using a fit to the $m_{4\ell}$ distribution. In the differential cross section measurements, given the low number of signal events expected in each bin, a simple cut-and-count method is used, subtracting the expected number of background events from the observed ones. The differential measurements are performed for several Higgs kinematic distributions, decay angles and jets-related variables. The measured cross sections, determined within a fiducial phase space and corrected for detection efficiency and resolution effects, are then compared to selected theoretical calculations of the SM expectations. No significant deviation from any of the tested predictions is found [6].

The measurement of the ZZ final state in the mass range above the $2m_Z$ threshold provides a unique opportunity to measure the off-shell couplings strength of the observed Higgs boson. Assuming an identical coupling strength for on- and off-shell Higgs boson production and decay, one can reinterpret these measurements as a constraint on the total width Γ_H/Γ_H^{SM}. Given the assumptions detailed in Ref.[7], the observed 95% CL limit is found to be: $4.8 < \Gamma_H^{95\%}/\Gamma_H^{SM} < 7.7$.

3 $H \to \gamma\gamma$

The $H \to \gamma\gamma$ channel offers a clean signature due to the excellent mass resolution in the diphoton final state, allowing the observation of a narrow mass peak over a smoothly falling background determined from data. The typical mass resolution is 1.7 GeV, while the s/b is approximately 3%.
Higgs boson candidates are selected by requiring two photons fulfilling tight identification criteria based on calorimeter shower shapes, isolation requirements and kinematic cuts. The diphoton invariant mass $m_{\gamma\gamma}$ is computed using the measured energies and their opening angle, estimated from the production vertex and the photon impact points in the calorimeter. The vertex is selected by an algorithm that exploits the longitudinal segmentation of the calorimeter and information from the tracks associated to each vertex. Thanks to a revised photon energy calibration [8], a 10% improvement is achieved on the expected mass resolution.
To improve the accuracy of the mass measurement, events are separated into ten categories with different s/b, invariant mass resolutions and systematic uncertainties. The Higgs boson mass is extracted from a simultaneous signal-plus-background fit to the mass spectra of all categories where the parameters associated to the background model are allowed to vary. The measured mass in $H \to \gamma\gamma$ is found to be: $m_H = 125.98 \pm 0.42(\text{stat}) \pm 0.28(\text{syst})$ GeV [4].

The available data also allow a measurement of the fiducial and differential cross section in this channel. The general strategy is similar to that already described for the $H \to 4\ell$ channel: signal yields are extracted in a fiducial volume and then corrected for the effects of detector inefficiency and resolution. In this case, the number of signal events is estimated using a fit to $m_{\gamma\gamma}$. Differential cross sections as a function of variables related to the diphoton kinematics and the jet activity are measured and found to be broadly in line with SM expectations [9].

An improved mass measurement is obtained from the combination of the new results available for the $H \to ZZ^* \to 4\ell$ and the $H \to \gamma\gamma$ channels. The compatibility between the mass measurements from the two individual channels is now at the level of 2.0σ. The final measurement, $m_H = 125.36 \pm 0.37(\text{stat}) \pm 0.18(\text{syst})$ GeV, has significantly improved systematic uncertainty and supersedes the previous result [4].

4 $H \to WW^* \to \ell\ell\nu\nu$

The $H \to WW^* \to \ell\ell\nu\nu$ channel has the highest rate among the bosonic decays and its s/b ratio is $O(10)$%, but it suffers from a limited mass resolution due to the presence of two neutrinos in the final state. The dominant backgrounds are *WW*, $t\bar{t}$ and *Wt*, all of which have two *W* bosons in their final state, *W+jets* and other diboson processes. In the analysis, events with two opposite-charge leptons and a large momentum imbalance from the neutrinos are split according to the jet multiplicity. This allows the control of the background from top quarks, as well as the extraction of the signal strengths for the ggF production process, populating mainly the 0- and 1-jet bin, and the VBF production process, ending up in the 2-jets category. An excess of events relative to the background-only expectation is observed at $m_H = 125.5$ GeV with a local significance of 3.8σ and a measured signal strength of $\mu = 0.99^{+0.31}_{-0.28}$ [10].

Studies of the spin and parity of the Higgs boson have been carried out in all three channels introduced so far, and subsequently combined. These studies have shown that the new particle's quantum numbers are compatible with the SM spin-parity $J^P = 0^+$, whereas all alternative hypotheses are excluded at confidence levels above 97.8% [11].

5 $H \to Z\gamma \to \ell\ell\gamma$

The observation of the $H \to Z\gamma \to \ell\ell\gamma$ is extremely challenging, due to the low cross section, close to that of the $H \to 4\ell$, and the large background, which result in a s/b ratio ranging from 0.01 to 0.001. The event selection requires two opposte-sign leptons and one photon, satisfying very similar requirements to those of the $H \to \gamma\gamma$ and $H \to 4\ell$ analyses. The main backgrounds originate from continuum $Z + \gamma$, $Z + \ell\ell$ production, and from radiative $Z \to \ell\ell\gamma$ decays. To improve the signal sensitivity of this analysis, the selected events are classified into eight categories with different centre-of-mass energies, lepton flavours, s/b ratios and invariant-mass resolutions. The presence of a signal is tested using a likelihood fit to the $m_{\ell\ell\gamma}$ spectra, where the signal and the background are modelled by analytical functions independently in the eight event categories. No excess with respect to the background is found, and upper limits have been set on the cross section times branching ratio. The 95% CL limit for a Higgs mass of $m_H = 125.5$ GeV is found to be 11 times the SM expectation [12].

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