Measurement of the Higgs boson properties using the ATLAS detector

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Abstract. With the proton-proton collision dataset collected at $\sqrt{s} = 13$ TeV with the ATLAS detector at LHC, an integrated luminosity of 139 $fb^{-1}$ has been achieved and detailed measurements of Higgs boson properties can be performed. The measurements of Higgs boson properties using various decay modes of the Higgs boson is presented. The different production mode cross sections are determined, simplified template cross sections are measured, and interpretations of the results in different frameworks are obtained.

1. Introduction
From the discovery of the Higgs boson claimed by the ATLAS [1] and CMS [2] experiment in 2012, several studies have been carried out to compare its properties with those predicted by the Standard Model (SM). The Higgs boson properties, as the couplings to SM fermions and bosons, can be studied in its main production processes, namely gluon fusion (ggF), vector boson fusion (VBF), associated production with W or a Z boson (WH, ZH) or with a pair of top quark (tH), as well in its decay modes $H \rightarrow ZZ$, $WW$, $\gamma\gamma$, $\tau\tau$, $bb$, $Z\gamma$ and $\mu\mu$.

During the Run 1, combined ATLAS and CMS measurements of the Higgs boson production and decay rates, as well as constraints on its couplings to vector bosons and fermions have been performed [3]. These results have been interpreted in terms of the signal strength, which is the ratio of the observed cross section ($\sigma$) times branching ratio ($BR$) with respect to the SM expected value. The production and decay rates of the Higgs boson can be also parametrised in the so-called $\kappa$-framework [4], computing the $\sigma \times BR$ quantities in terms of the couplings modifiers $\kappa$, defined as scale factors to the cross sections or to the partial widths.

With the increasing statistics of the Run 2 up to 139 $fb^{-1}$, large improvements on the precision of the property measurements has been achieved, like on the mass, the spin and the width, as well on the fiducial differential cross section measurements and the production cross section. In this round the results has been interpreted via theoretical frameworks (EFT, Pseudo-Observable, etc.) on top of the $\kappa$-framework to put constraints on anomalous couplings of the Higgs boson with the other SM particles and to probe New Physics phenomena.

2. Higgs boson precision measurements
2.1. Higgs boson mass
The Higgs boson mass measurement has been performed in two of the most sensitive channels $H \rightarrow ZZ^* \rightarrow 4l$ and $H \rightarrow \gamma\gamma$, due their clear signature and a mass resolution of 1-2%. Due to their low BR, the total uncertainties on the mass measurement are dominated by the statistical
term, and the systematic ones by the experimental effects related to the muon momentum and photon energy scales. The results in the two channels with the partial Run 2 statistics of 36 fb$^{-1}$ has been combined with the Run 1 results to obtain the combined measurement of the Higgs boson mass: $m_H = 124.97 \pm 0.24$ (±0.16) GeV [5] (as shown in figure 1). Preliminary mass measurement in $H \rightarrow ZZ^* \rightarrow 4l$ channel with the full Run 2 statistics has been published: $m_H = 124.92^{+0.21}_{-0.20}$ GeV [6], showing an improvement of about 40% on the mass resolution with respect to the previous round of the analysis in this channel.

2.2. Spin-CP

A test of CP invariance has been performed in the $H \rightarrow \gamma \gamma$ and $H \rightarrow \tau \tau$ decay channels. In the $H \rightarrow \gamma \gamma$ decay, the $ttH$ production vertex has been studied to put a strong constraint on possible CP-odd couplings between the Higgs boson and the top quark, excluding a pure CP-odd coupling at 3.9 σ and a mixing angle $|\alpha| < 43^\circ$ [7]. In figure 2, the observed 2D likelihood contours for $\kappa_\ell \cos(\alpha)$ and $\kappa_\ell \sin(\alpha)$ are shown.

In the $H \rightarrow \tau \tau$ decay the coupling between the Higgs boson and the vector boson has been investigated in the VBF production vertex and described in an Effective Field Theory framework. The parameter $d$ represents the strength of CP violation and it has been constrained to the interval [-0.090,0.035] at the 68% CL, based on the fit of Optimal Observable distribution (figure 3), a matrix element based variable able to discriminate CP-odd contribution [8].

2.3. Higgs Width

A direct measurement of Higgs width is limited by the experimental resolution which is orders of magnitude greater than the one needed for the measurement. The $H \rightarrow ZZ^*$ decay channel sets a constraint on the Higgs boson width, obtained by measuring the off-shell Higgs boson production event yields normalised to the on-shell one $\mu_{\text{off-shell}}/\mu_{\text{on-shell}}$, assuming identical coupling modifiers for on-shell and off-shell Higgs boson. The combined results in the $ZZ^* \rightarrow 4l$ and $ZZ^* \rightarrow 2l2\nu$ decay channels set an observed (expected) upper limit on the off-shell signal strength $\mu_{\text{off-shell}} < 3.8$ (3.4) at 95% CL and on the Higgs width the observed (expected) limit is $\Gamma_H/\Gamma_{H}^{\text{SM}} < 3.5$ (3.7) at 95% CL.

![Figure 1](image1.png) **Figure 1.** Measured values of the Higgs boson mass for the Run 1 2D likelihood contours for $H \rightarrow \gamma \gamma$, as well as their combined results [5].

![Figure 2](image2.png) **Figure 2.** The observed 2D likelihood curves as function of $\kappa_\ell \cos(\alpha)$ and $\kappa_\ell \sin(\alpha)$ [7].

![Figure 3](image3.png) **Figure 3.** The observed Higgs boson mass for the Run 1 2D likelihood contours for $H \rightarrow ZZ^* \rightarrow 4l$ and $\mu_{\text{off-shell}}/\mu_{\text{on-shell}}$ [5].
3. Fiducial Differential cross section measurements
Differential cross section measurement have been performed on several variables sensitive to the Higgs boson properties. In particular in the four lepton decay observables related to the four leptons kinematics sensitive for testing the Higgs CP properties, like for example angles between decay leptons, have been unfolded. The distribution has been unfolded, to correct for detector level effects, in a fiducial phase space based on detector acceptance to minimise the model dependency. The first results with the full Run 2 statistics have been published from the \( H \to ZZ^* \to 4l \) [10] and \( H \to \gamma\gamma \) [11] decay channels analysis, and no significant deviation from any of the tested predictions have been found, as can be seen in figure 4 and figure 5.

These results have been interpreted in different theoretical framework. The measured differential fiducial cross sections in the \( H \to ZZ^* \to 4l \) has been used to probe possible effects of physics beyond the SM within the framework of Pseudo-Observables, using the \( m_{12} \) vs. \( m_{34} \) double differential section to study the modified contact terms between the Higgs boson, the Z boson and the left- or right- handed leptons [10]. In the \( H \to \gamma\gamma \) decay channel the differential cross sections of \( p_T^{\gamma\gamma}, N_{jets}, m_{jj}, p_T^{l1} \) and \( \Delta\phi_{jj} \) have been used to constrain the Wilson coefficients of the operators of the Higgs Effective Lagrangian in the Strong Interacting Light Higgs basis (SILH) and the operators of the SMEFT Lagrangian in the Warsaw basis (SMEFT) [11]. Finally, both the analysis have used the Higgs \( p_T \) spectrum to constrain the Yukawa couplings of the Higgs boson with the charm quark, which affects the low-\( p_T \).

The limits obtained from the two analysis at 95% CL are:

\[
H \to ZZ^* \to 4l : \kappa_c = [-12,11] @ 95\% \text{ CL} \quad [10]; \quad H \to \gamma\gamma : \kappa_c = [-19,24] @ 95\% \text{ CL} \quad [11] \quad (1)
\]

In figure 6 the observed limits at 95% CL on Yukawa couplings \( \kappa_c \) and \( \kappa_b \) using only the \( p_T^{4l} \) shape has been used to constrain \( \kappa_c \) and \( \kappa_b \) [10].

4. Production cross section measurements
The production cross section measurements represent a good way to probe the strength of the Higgs boson coupling with the other Standard Model particles and test possible beyond...
SM effects. A way to perform this measurement is in the *Simplified Template Cross Section* framework (STXS) [12], defining exclusive regions of the Higgs phase space (called STXS bins) based on its kinematics and of the particle and jets produced in association to identify the different production modes: \( p_T^H, N_{jets}, m_{jj}, p_T^V \). The definitions of the STXS bins are motivated by maximising the experimental sensitivity and minimising the dependency on theoretical uncertainties. Different STXS Stages can be defined, corresponding to increasingly fine granularity, but not all the analyses are sensitive to all the STXS bins. The STXS measurement is performed defining a reco-level categorisation, which is chosen as close as possible to the STXS one to minimise the extrapolation dependency.

4.1. Individual channel measurements

The \( H \to \gamma\gamma \) [13] analysis has provided 27 STXS measurements, based on the so called Stage 1.2. The reco events have been categorised in 88 categories, using Multiclass BDT to discriminate different production modes, a simple BDT in each production category to discriminate the signal from the continuous background and fitting \( m_{\gamma\gamma} \) to extract the signal. The STXS bins measurements show a good compatibility with SM. The cross section in each production mode show a compatibility with a p-value of 3%, due to a large anti-correlation between the \( WH \) and \( ZH \) production (as shown in figure 7). Then also the \( VH \) combined cross section has been reported: \( \sigma_{VH} = 5.9 \pm 1.4 \) fb, compatible with the expected value of \( 4.53 \pm 0.12 \) fb.

In \( H \to ZZ^* \to 4l \) [14] analysis 12 STXS bins has been measured, using 12 reco categories for the signal and further 5 categories defined in the \( m_{4l} \) sideband to constrain the \( ZZ^* \) background. In this case a Neural Network has been used as discriminant in each category and also as fitting observable. Also in this case a good compatibility both in the production cross section (shown in figure 8) and in the STXS results has been found. Furthermore this results has been used to put constraint on anomalous CP–even and CP–odd couplings of the Higgs in the EFT framework.

In the \( H \to bb \) decay the \( VH \) production has been studied [15], performing 5 STXS measurements. Also in this analysis a BDT has been used to discriminate the \( VH \) signal from the background process and as fitting observable, in each of the 42 reco categories, 14 as Signals Regions and the others as Control Regions to estimate the \( V+jets \) and \( tt \) backgrounds. The \( VH \) production in this decay channel has been found with an observed significance of \( 6.7 \sigma \) (shown in figure 9). Also in this case constraints in the EFT couplings have been defined, much more stringent with respect to the \( H \to ZZ^* \to 4l \) results.

Figure 7. Observed cross section times branching ratio in \( H \to \gamma\gamma \) for the main production mode, normalised to the SM predictions [10].

Figure 8. Observed cross section times branching ratio of the signal strength \( \mu_{VH}^{bb} \) in \( H \to ZZ^* \) for the main for \( WH \) and \( ZH \) and their production mode, normalised combination [10], to the SM predictions [11].

Figure 9. Fitted values of the decay width of the signal strength in \( H \to bb \) for the expected values [15].
In the $H \to WW^* \to e\nu\mu\nu$ decay channel, a first analysis has been performed with 36 fb$^{-1}$ targeting $ggF$ and $VBF$ production cross section measurement. The events have been categorised on the basis of the number of jets and a BDT has been used in the $VBF$ category. The measured cross sections in the two production modes are: $\sigma_{ggF} \cdot B_{H \to WW^*} = 11.4^{+2.2}_{-2.1}$ pb and $\sigma_{VBF} \cdot B_{H \to WW^*} = 0.50^{+0.29}_{-0.28}$ pb, compatible with the expected values $10.4 \pm 0.6$ pb for the $ggF$ and $0.81 \pm 0.02$ pb for the $VBF$. The observed $ggF$ and $VBF$ signals have significance of $6 \sigma$ and $1.8 \sigma$ respectively. Preliminary analysis with the full Run 2 statistics to perform the $VBF$ production cross section, improved the significance of the measurement, using a dNN instead of a BDT to discriminate the $VBF$ signal. The new measurement $\sigma_{VBF} \cdot B_{H \to WW^*} = 0.85^{+0.20}_{-0.17}$ pb reaching an observed significance of $7 \sigma$, and representing the first observation of $VBF$ in $H \to WW^*$.

In $H \to \tau\tau$ decay channel the $ggF$ and $VBF$ production cross sections have been measured with 36 fb$^{-1}$, categorising the events on the basis of the number of jets $\geq 2$ for the $VBF$ signal and high-$p_T^H$ for the $ggF$. The measurement is performed by fitting the $m_{\tau\tau}$ distribution, and resulting cross sections are $\sigma_{ggF} = 3.1 \pm 1.0$(stat.)$^{+1.6}_{-1.3}$(syst.) pb and $\sigma_{VBF} = 0.28 \pm 0.09$(stat.)$^{+0.11}_{-0.09}$(syst.) pb.

Finally several searches in unobserved Higgs decay channels have been performed with Run 2. The invisible Higgs decay [$19$] is a way to probe a possible decay in WIMPs. Assuming a Standard model cross section, an upper limit has been set on the branching ratio: $B_{inv} < 0.13$ at 95% CL. The $H \to Z\gamma$ [$20$] and $H \to \mu\mu$ [$21$] have been studied with the full Run 2 statistics and modest observed (expected) significances have been found of $2.2 (1.2) \sigma$ and $2 (1.7) \sigma$ respectively in the two decays.

5. Combination of measurements of Higgs boson production and decay

The combination of the production cross section measurements in the main processes $ggF$, $VBF$, $WH$, $ZH$ and $ttH + tH$ has been performed (as shown in figure [$22$], based on the analyses presented in the previous section). The observed significance in each production mode is larger than $5 \sigma$. Also the STXS (Stage 1.2) measurements has been performed and the results show a compatibility with the SM expectation of 95%. On the $tH$ STXS measurement an upper limit $< 8.4 \times 10^{-3}$ has been set.

5.1. Interpretation

These results has been interpreted in the well-known $\kappa$-framework. An interpretation assuming a universal coupling of vector bosons and fermions $\kappa_V$ and $\kappa_F$ has been performed, and also considering the coupling strength to $W$, $Z$, $t$, $b$, $\tau$ and $\mu$ independently. To probe BSM effect in the loop, the modified couplings with gluons $\kappa_g$ and photons $\kappa_\gamma$ have been studied. They may contribute to the total Higgs width, which is sensitive to possible invisible decay ($B_{inv}$) and undetected decay ($B_{di}$). The different constraints are put on the couplings based on the different assumptions that have been made. The best-fit values of the Higgs boson coupling modifiers including effective photon and gluon couplings with and without BSM contributions to the total width are shown in figure [$23$]. Finally an interpretation on possible SM extension as the Two-Higgs-doublet models (2HDMs) has been performed, putting constraint on possible BSM couplings of the two Higgs doublets that can couple in different way, based on the model, in which one Higgs doublet couples to vector bosons and the other to fermions (as Type-I model show in figure [$24$] or one doublet couples to up–type quarks and the other to down–type quarks and charged leptons (as Type-II model).
6. Conclusion

The increase in integrated luminosity with Run2 lead to a lot of improvements in the precision of the Higgs boson property measurements and predicted Standard Model processes have been observed for the first time. All the measurements show a good agreement with the expectation and also several constraints on possible BSM couplings of the Higgs boson has been set with several analyses. Recently the production cross section measurements in different decay channels have been combined showing a significance larger than 5 $\sigma$ in the main production modes. The VBF production in $H \to WW^*$ has been observed for the first time with a significance of 7 $\sigma$ and the most rare Higgs decays in $Z\gamma$ and $\mu\mu$ have been observed with a significance of 2 $\sigma$ and 2.2 $\sigma$. Several analyses are on going using the full Run 2 dataset and then new results are expected.

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