

Measurements of the Higgs Boson Properties at the ATLAS Experiment

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Abstract. Measurements sensitive to the Higgs boson production and decay performed at the Large Hadron Collider by the ATLAS experiment are reviewed. They are based on the analyses of 13 TeV proton-proton collision data collected between 2015 and 2017, corresponding to integrated luminosities ranging from 36 to 80 fb⁻¹. Different analyses are discussed and the combined constraints on the Higgs boson couplings are also summarised.

1. Introduction

After the discovery of the Higgs boson in 2012 [1, 2] by the ATLAS [3] and CMS Collaborations [4] at the Large Hadron Collider (LHC), the focus has shifted to measurements of its properties to test the predictions of the Standard Model (SM). This report presents the results on the Higgs boson measurements by ATLAS using data from LHC Run 2, started in 2015 at a centre of mass energy of 13 TeV proton-proton collisions. The measurements are based on either data collected between 2015 and 2016, corresponding to an integrated luminosity around 36 fb⁻¹, or on data collected between 2016 and 2017, corresponding to an integrated luminosity around 80 fb⁻¹. This large dataset allows to improve the measurements done during the Run 1 (2011-2012) and to observe all of the main production modes and direct couplings to bottom and top quarks. The latest combinations of Higgs boson measurements are also discussed.

2. Higgs boson production and decay

The predicted production cross sections [5] for the Higgs boson discussed in the following assume a proton-proton collision energy of 13 TeV and a Higgs boson mass of 125 GeV. The process with the higher cross section is the gluon-gluon fusion (ggF) process, which produces a Higgs boson via a gluon induced loop of heavy particles. This production channel has a cross section of 48.6 pb. The second largest production channel is vector boson fusion (VBF) with a production cross section of 3.8 pb. In this production mode two W or Z bosons, radiated off the quarks in the protons, fuse together to form a Higgs boson. In the associated production with a vector boson (VH), the Higgs boson is produced by being radiated off from a W or Z boson. The production cross sections are 1.4 pb for WH and 0.9 pb for ZH production. The less likely production channel is the $t\bar{t}H$ production, where the Higgs boson is produced in association with a top-quark pair. This production channel has a production cross section of 0.5 pb.

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The most probable decay is the one into a pair of bottom quarks with a branching ratio (BR) of 58%. Despite of high BR, this channel is very difficult experimentally due to a huge background and it is not possible to see it, for example, via the ggF mechanism. However, one can try to extract that signal in the VH or $t\bar{t}H$ production modes. The decay into a pair of W bosons has the second largest BR of 21%. The fully leptonic decay ($WW^* \rightarrow \ell\nu\ell\nu$) is the more accessible channel although it does not allow to reconstruct a Higgs boson mass. Decays into other bosons or lighter fermions have decay rates below 10%. The cleanest decay channels, where also the Higgs boson mass reconstruction is possible, are $H \rightarrow \gamma\gamma$ ($BR \sim 2.3 \times 10^{-3}$) and $H \rightarrow ZZ^* \rightarrow 4\ell$ ($BR \sim 1.3 \times 10^{-4}$).

3. Higgs boson decays to bosons

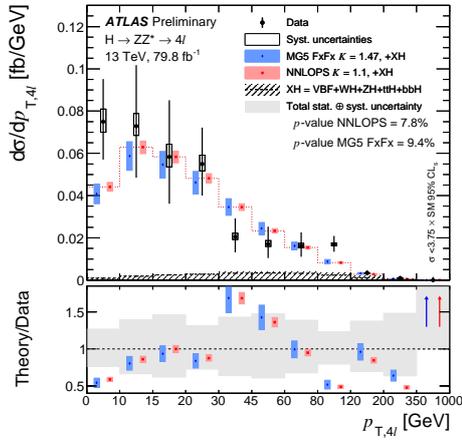
The signature in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay channel is two isolated opposite-sign leptons (electrons or muons) and sizeable missing transverse energy due to neutrinos. The results [6] are based on a 36 fb^{-1} datasets; only the $e\mu$ final state is considered. The events are subdivided in accordance with the number of jets (0, 1 or ≥ 2). For the 0 and 1 jet cases the ggF mechanism is expected to be dominant while for ≥ 2 jets case signal events are mostly due to the VBF mechanism. The observed (expected) signal significance for the ggF production is 6.0σ (5.3σ), respectively. The ggF cross section multiplied by $BR(H \rightarrow WW^*)$ is measured to be $11.4^{+2.1}_{-2.2}$ pb, in agreement with the theoretical prediction 10.4 ± 0.6 pb. The measured signal strength in the SM units (μ) is $1.10^{+0.21}_{-0.20}$. The observed (expected) signal significance in the VBF production mode is 1.8σ (2.6σ), and the measured cross section is $0.50^{+0.29}_{-0.28}$ pb, compatible with the expected value of 0.81 ± 0.02 pb. The corresponding measured signal strength is $\mu = 0.62^{+0.36}_{-0.35}$.

Decays of the Higgs boson into a pair of photons ($H \rightarrow \gamma\gamma$) or in four leptons via $H \rightarrow ZZ \rightarrow 4\ell$ ($\ell =$ electrons or muons) have final state particles that can be measured with a good experimental resolution and have almost only one well modelled background source ($\gamma\gamma$ continuum and ZZ production). In both channels the fiducial cross section, measured within a phase space close to the geometrical acceptance of the detector, has been measured [7, 8]. In the $H \rightarrow ZZ \rightarrow 4\ell$ decay it is found to be $4.04 \pm 0.41(stat.) \pm 0.22(syst.)$ fb, in agreement with the SM prediction of 3.35 ± 0.15 fb. In the $H \rightarrow \gamma\gamma$ channel, the cross section is found to be $60.4 \pm 6.1(stat.) \pm 6.0(syst.)$ fb while the expected SM value is 63.5 ± 3.3 fb. With the increased data statistics it was possible to perform also differential fiducial cross section measurements in the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4\ell$ decay channels [7, 8]. Differential measurements are sensible to beyond SM Higgs interactions that might be hidden in measurements of the total cross sections. Figure 1 shows the measurement of the Higgs boson transverse momentum in the di-photon and 4 lepton decay channels using data corresponding to 80 fb^{-1} . The measurements are compared to different theoretical predictions, which are found to be compatible with the data within the uncertainties. Figures 2 and 3 show the measured cross sections multiplied by the decay branching ratios in the different production modes. The numbers are normalised to the SM predictions. A nice agreement between the measurements and the theory is observed.

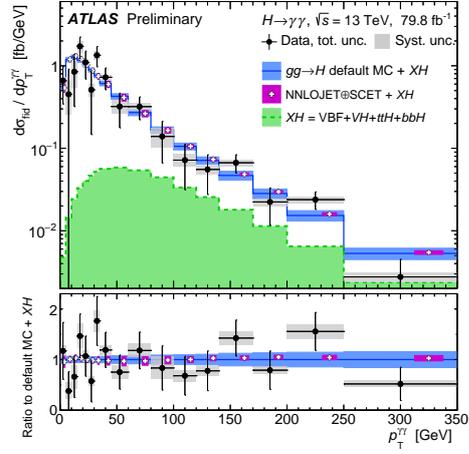
The Higgs boson mass (m_H) is extracted from the invariant mass of the photon pairs or the 4 leptons and is measured to be 124.93 ± 0.40 GeV and 124.79 ± 0.37 GeV respectively [9]. Both measurements were obtained using 36 fb^{-1} . Figure 4 shows the invariant mass spectra in both analysis channels. The combination of those two Run 2 measurements and the Run 1 measurements gives $m_H = 124.97 \pm 0.24$ GeV.

4. Fermion couplings

During the Run 1, LHC experiments successfully observed Higgs boson couplings to W , Z and γ bosons while the only coupling to fermions observed was that to τ -leptons, confirmed also with Run 2 data [10]. Establishing Higgs boson couplings to other fermions was one of the goals for Run 2.



(a)



(b)

Figure 1: Differential fiducial cross sections for the transverse momentum of the Higgs boson in the 4 lepton [7](a) and di-photon [8] (b) decay channels. Data (black points) are compared to several theoretical predictions.

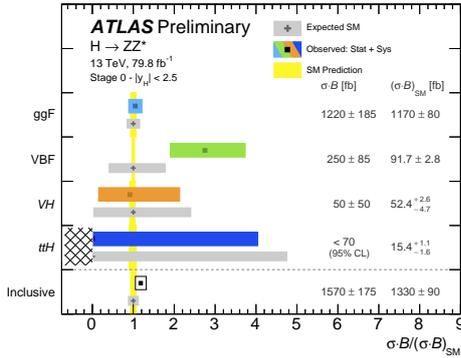


Figure 2: Measured production mode cross sections times the Higgs branching ratio for the 4 lepton [7] decay channel. The central values and uncertainties have been divided by their SM expectations. The uncertainties in the predicted SM cross sections are shown with a yellow band.

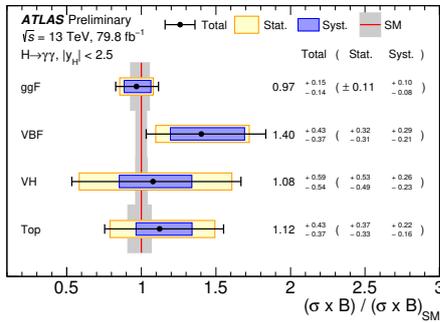


Figure 3: Measured production mode cross sections times the Higgs branching ratio for the di-photon [8] decay channel. The central values and uncertainties have been divided by their SM expectations. The uncertainties in the predicted SM cross sections are shown with a gray band.

The coupling of the Higgs boson to the heaviest known SM particle, the top quark, can only be probed directly in the ttH production channel. Different analyses are performed to target the different Higgs boson decay modes: $H \rightarrow \gamma\gamma$, multi-leptons, $H \rightarrow ZZ \rightarrow 4l$ and $H \rightarrow b\bar{b}$ [11]. The first two channels are those with the with the largest sensitivity. Their respective observed (expected) significances are 4.1(3.7) σ using 80 fb⁻¹ of 13 TeV data and 4.1(2.8) σ using 36 fb⁻¹

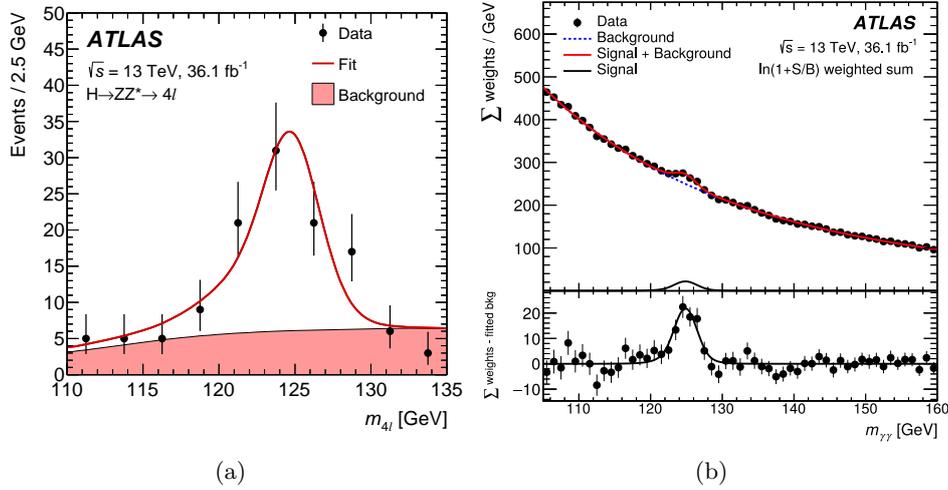


Figure 4: The invariant 4 lepton mass (a) and di-photon mass (b) from the $H \rightarrow ZZ \rightarrow 4\ell$ and the $H \rightarrow \gamma\gamma$ analyses [9]. In (a), the invariant mass distribution for the data (black points) are shown together with the simultaneous fit result to $H \rightarrow ZZ \rightarrow 4\ell$ candidates (continuous line). The background component of the fit is also shown (filled area). In (b), the di-photon invariant mass distribution from data (black points) is overlaid with the result of the fit (solid red line). The blue dotted line describes the background component of the model.

of 13 TeV data. Combining the different decay modes above, and also the Run 1 analyses, the observation of the $t\bar{t}H$ is established with an observed (expected) significance of $6.3(5.1) \sigma$ and the measured signal strength μ is $1.32 \pm 0.18(stat.)^{+0.21}_{-0.19}(syst.)$. Figure 5 shows the measured signal strengths in the different decay channels as well as their combination, which are all compatible with the SM expectations.

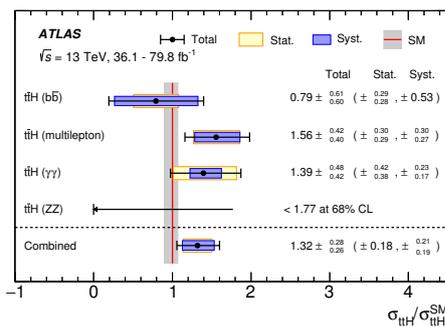


Figure 5: $t\bar{t}H$ production cross sections divided by the SM prediction [11]. Measurements (black points) are shown together with the statistical and systematic uncertainties (horizontal bands). The red vertical line indicates the SM cross-section prediction while the grey band represents the theoretical uncertainties on this prediction.

The decay of the Higgs boson to a pair of bottom quarks is the decay channel with the highest probability but it is experimentally challenging because of the high amount of background processes with hadronic signatures. The most sensitive channel targets the VH associated production [12], but the $t\bar{t}H$ [13] and VBF [14] production modes also contribute. In each analysis, b -jets are identified using a multivariate algorithm that discriminates b -jets from non- b -jets. The VH production mode provides the best sensitivity since the decay of the associated W or Z boson to leptons suppresses the multi-jet background and provides a good trigger signature. This analysis probes three different final states (0, 1 and 2-lepton channels) and employs a multivariate algorithm that separates signal from background events. The expected

sensitivity with the combined Run 1 data and the Run 2 dataset corresponding to 80 fb^{-1} of the VH , $H \rightarrow b\bar{b}$ production is 5.1 (4.8) σ . After combining the VH search with the searches in the other production modes, the $b\bar{b}$ decay mode is observed at a significance of 5.4σ . The VH , $H \rightarrow b\bar{b}$ search, after combination with the other searches for VH production in different decay modes, also provides the observation of the VH production mode with an observed significance of 5.3σ [12]. Figure 6 summarises the measured signal strengths of the individual $H \rightarrow b\bar{b}$ and VH analyses as well as their combination. In all cases the measurements are compatible with the SM expectations.

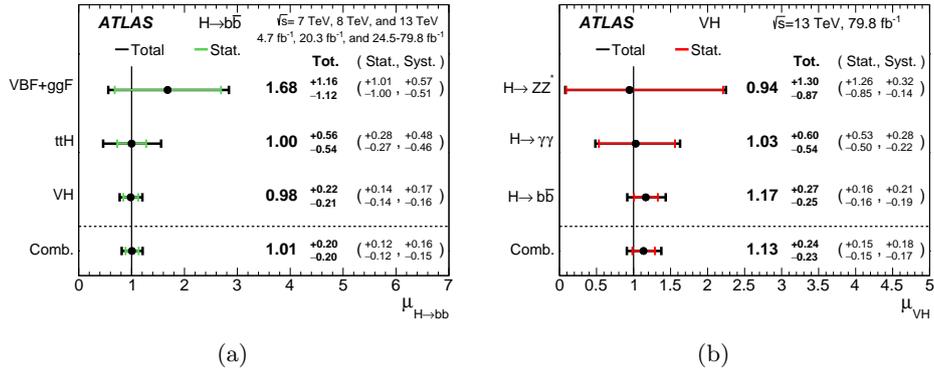


Figure 6: The measured values of the Higgs boson signal strength $\mu_{H \rightarrow b\bar{b}}$ (a) and μ_{VH} (b) for the individual analyses and their combination [12]. Measurements (black points) are shown together with the statistical and systematic uncertainties (horizontal lines). The black vertical line indicates the SM cross-section prediction.

5. Combination of Higgs boson measurements

The combination of the ATLAS Higgs boson measurements using up to 80 fb^{-1} of Run 2 data includes all the main Higgs boson production modes and decays to $\gamma\gamma$, ZZ , WW , $\tau\tau$, $b\bar{b}$ and $\mu\mu$ [15]. The measured signal strength with respect to the SM expectation is $\mu = 1.13^{+0.09}_{-0.08}$ [16].

Measurements of the Higgs boson couplings and sensitivity to physics beyond the Standard Model can be achieved using the κ framework [17], in which the same coupling structure as in the SM is assumed and the couplings are just scaled by coupling modifiers κ_i . Figure 7 shows the constraints on the effective couplings to fermions and bosons from the ATLAS analyses [16]. All Higgs boson couplings to vector bosons are assumed to scale by the same factor κ_V and similarly for the couplings to fermions with the scale factor κ_F . Loops are resolved assuming the SM content and no other new physics contribution. The total Higgs boson width is also computed assuming no invisible or undetected decay modes. The data are consistent with the SM predictions. Figure 8 shows how the measured coupling modifiers vary with the mass of the particle the Higgs boson couples to [16]. Separate modifiers for couplings to vector bosons (κ_W , κ_V) and to fermions (κ_b , κ_t , κ_τ , κ_μ) are assumed. All measurements are compatible with the SM expectation that the coupling strengths modifiers scale linearly with the particle mass.

6. Conclusions

The latest Higgs boson measurements of the ATLAS experiment using up to 80 fb^{-1} of LHC proton-proton collisions at 13 TeV are presented. No significant deviations from the SM expectation are observed. The Higgs boson is now observed in all the main production modes

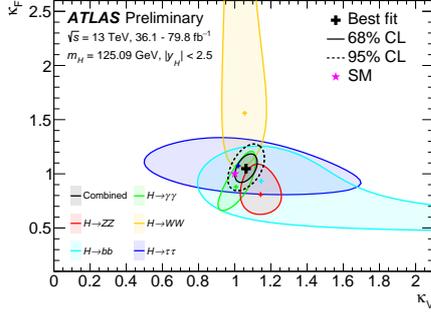


Figure 7: Observed contours at 68% and 95% CL in the (κ_F, κ_V) plane for individual channels and the combined fit [16]. The crosses indicate the best-fit values and the star the SM prediction.

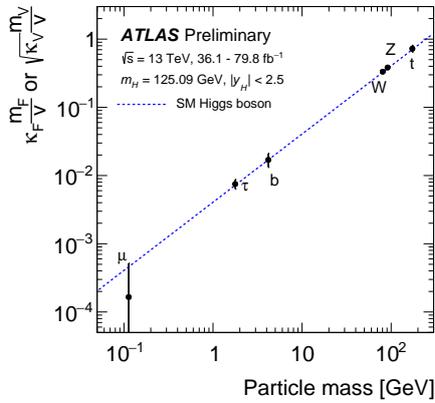


Figure 8: Coupling strength modifiers for fermions ($F = t, b, \tau, \mu$) and for weak gauge bosons ($V = W, Z$) as a function of their masses [16]. The SM prediction for both cases is also shown (dotted line).

(ggF , VBF , VH , $t\bar{t}H$) and in five different decay channels ($\gamma\gamma$, ZZ , WW , $\tau\tau$, $b\bar{b}$). The mass of the Higgs boson is measured to be 124.97 ± 0.24 GeV. In addition to the recently achieved observations of the $b\bar{b}$ decay, VH and $t\bar{t}H$ production, the ATLAS experiment also performed production cross section and fiducial differential measurements in the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4\ell$ channels.

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