Review of Standard Model Higgs results at the
ATLAS experiment

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Abstract. The investigation of the mechanism of electroweak (EW) symmetry breaking has been one of the main goals of the ATLAS experiment [1] research program at the CERN Large Hadron Collider (LHC). In the Standard Model (SM) of particle physics, the breaking of the EW symmetry is realised by introducing a complex doublet scalar field which is related to the existence of a neutral particle, the Higgs boson. The Higgs scalar field is responsible of the mass of the other particles; the mass of its mediator, the Higgs boson, is the only free parameter in the theory. In 2012, the ATLAS and CMS collaborations discovered a new particle consistent with the SM Higgs boson and two years later measured its mass, in the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$ channels, to be $m_H = 125.09 \pm 0.21 \text{ (stat) } \pm 0.11 \text{ (sys)} \text{ GeV}$ with data collected in 2011 and 2012 (LHC Run 1). This document will cover the SM Higgs analyses performed with approximately 15 fb$^{-1}$ of $pp$ collision data collected until summer 2016 during the so-called Run 2 LHC data-taking at a center-of-mass energy ($\sqrt{s} = 13 \text{ TeV}$).

The documents will be structured as follows. Section 1 will describe the measurement of the Higgs boson properties in the bosonic decay channels ($H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$ leptons), while Section 2 will focus on the searches in the fermionic final states ($H \rightarrow b\bar{b}, t\bar{t}H$ and $H \rightarrow \mu\mu$). Finally, conclusions will be discussed in Section 3. There is also a vast number of di-Higgs searches, reported for example in References [9] and [10]. However, the signal sensitivity is still small and they will not be detailed in this document. The dominant Higgs boson production modes are gluon-gluon fusion (ggF), vector boson fusion (VBF), production in association with a vector boson $V$ ($VH$, $V=W$ or $Z$) and in association with top quarks ($t\bar{t}H$). The most sensitive Higgs boson decay channels at the LHC are the modes $\gamma\gamma$, $ZZ^* \rightarrow 4l$, $WW^*$, $\tau\tau$ and $b\bar{b}$. In addition, the production channel with the association of top quarks is of particular interest in order to study the top-Yukawa coupling.

1. Higgs decay to bosons
1.1. $H \rightarrow \gamma\gamma$
Measurements of the Higgs boson properties have been performed in the $H \rightarrow \gamma\gamma$ channel using 13.3 fb$^{-1}$ of proton-proton collisions data at $\sqrt{s} = 13 \text{ TeV}$ [2]. The Higgs boson decay into photons, through a loop of heavy particles, is an important channel in order to study the properties of the Higgs boson. Although this is featured by a small branching ratio, a very large yield can be obtained with a narrow peak on top of a smoothly falling background.

1.1.1. Object definition and analysis selection. Photon reconstruction is based on energy clusters in the electromagnetic calorimeter with transverse energy larger than 2.5 GeV in
\[ \Delta \eta \times \Delta \phi = 0.075 \times 0.125. \] The reconstruction is optimized to separate electrons, unconverted photons and converted photons. The photon energy is then corrected using calibration factors that are extracted both from simulation and data. The photon identification relies on the information of the lateral and longitudinal shape of the electromagnetic shower in the calorimeter. Photon candidates are required to exhibit a lateral shower shape consistent with that from a single electromagnetic shower and to deposit only a small fraction of their energy in the hadronic calorimeter. The selection criteria applied to such photons require them to be isolated with transverse momentum greater than 0.35 \( m_{\gamma\gamma} \) and 0.25 \( m_{\gamma\gamma} \) and each with pseudorapidity smaller than 2.37 excluding the region \( 1.37<\eta<1.52 \). The diphoton candidate pair is defined by seeding the two photon candidates with the highest transverse energy. Starting from this pair, a neural-network algorithm based on track and primary vertex as well as on the pointing information from the electromagnetic calorimeter identifies the diphoton primary vertex among all reconstructed vertices.

1.1.2. Signal and background modelling

The Higgs boson signal is extracted by employing a maximum-likelihood fit to the diphoton invariant mass spectrum in the range \( 105 < m_{\gamma\gamma} < 160 \) GeV. The signal contribution to the fit is modelled as a double-sided Crystal Ball function centered on the previously measured Higgs boson mass of \( m_H = 125.09 \) GeV. Due to the narrow width of the Higgs boson, the shape of this distribution is entirely driven by the energy and angular resolutions of the photons. The parameters of the model are extracted using a fit to a simulated \( H \rightarrow \gamma\gamma \) sample. The background is dominated by irreducible non-resonant \( \gamma\gamma \) production and reducible \( \gamma+\text{jets} \) and di-jet production.

1.1.3. Measurements of the fiducial, differential production cross sections and signal strengths

The Higgs boson fiducial cross section has been measured for different phase spaces which are sensitive to the inclusive Higgs boson production, to the vector boson fusion (VBF) production and to the Higgs boson production in association with a vector boson (VH). An unbinned maximum likelihood fit is performed on the di-photon invariant mass spectrum in each of the fiducial regions defined above. The extracted cross section is also corrected to account for detector effects. The inclusive fiducial cross section is \( \sigma_{\text{fid}} = 43.2 \pm 14.9 \) (stat) \pm 4.9 (syst) fb for a Higgs boson of mass 125.09 GeV decaying to two photons. The Standard Model predicts \( \sigma_{\text{SM}} = 62.8 \pm 3.4 \) (stat) \pm 4.4 (syst) fb when employing the same fiducial region.

The differential cross sections are measured as a function of the diphoton transverse momentum, the rapidity of the diphoton system, the cosine of the angle between the beam axis and the photons in the Collins-Soper frame of the Higgs boson, the jet multiplicity, the transverse momentum of the leading jet, the azimuthal angle between the leading two jets and the invariant mass of the leading two jets. The differential cross section as a function of the jet multiplicity exhibits an overall good agreement between data and the Standard Model predictions constructed from the highest perturbative QCD order available (NNLO + Parton Shower).

The event selected in the diphoton analysis are divided into exclusive categories that are optimised to enhance the separation of the various Higgs boson production processes. Each category is enriched with events of a given production mode. Two \( t\bar{t}H \) categories are defined for events in which at least one top quark decays leptonically or in which both top quarks decay hadronically. Five categories are enriched in Higgs boson production in association with a vector boson: the VH dilepton category targets ZH production with Z decaying in leptons, the VH one-lepton production targets WH production with W \( \rightarrow l\nu \), the VH missing transverse momentum category targets ZH production with Z \( \rightarrow \nu\nu \) and W \( \rightarrow l\nu \). Finally, one hadronic category targets VH production with a hadronically decaying vector boson. Two categories are created to enhance
the contribution of Higgs boson production through vector boson fusion. The remaining events populate the untagged category and they are split into four additional sub-categories which contain events produced through gluon fusion. Figure 1 reports the invariant mass distributions for all categories combined. Each of them is weighted by the signal-to-background ratio of the event category to which it belongs. The statistical procedure to extract the signal yield and the cross section in each category relies on a maximum likelihood fit to the $m_{\gamma\gamma}$ spectrum. The signal strength $\mu$, defined as the ratio of the measured cross section for a given category and the one predicted by the Standard Model for a given Higgs boson mass are shown in Figure 2 in addition to the global signal strength measured in Run 1. No significant deviations from the Standard Model expectations are observed.

1.2. $H \rightarrow ZZ^* \rightarrow 4l$

The Higgs boson decay to four leptons, $H \rightarrow ZZ^* \rightarrow 4l$ where $l=e, \mu$, provides a good sensitivity for the measurement of its properties due to the very clean final state with electrons and muons. The largest background of the analysis throughout the full four-lepton invariant mass ($m_{4l}$) spectrum is represented by the continuum ZZ production. For $m_{4l} > 160$ GeV there are also contributions from Z+jets and $t\bar{t}$ with two prompt leptons while the additional charged lepton candidates faking the signal arise from the decay of $b$ or $c$ quarks or from mis-identification of jets. The inclusive total and fiducial cross section measurements have been extracted with 11.6 fb$^{-1}$ collected in the 2015 and 2016 data taking periods [3].

1.2.1. Object definition and analysis selection

Electrons are reconstructed using information from the inner detector (ID) and the electromagnetic calorimeter. Electron candidates are built from clusters of energy associated with ID tracks. Background discrimination is based on shower shape information available from the highly segmented calorimeter, high-threshold transition radiation tracker (TRT) hits as well as compatibility of the tracking and calorimeter...
Figure 2. Production signal strength measured for the different Higgs boson production processes (gluon fusion, VBF, VH, tth) and globally (Run 2) compared to the signal strength measured at 7 and 8 TeV (Run 1). The error bar shown is the total uncertainty [2].
different model assumptions.

In addition to the fiducial cross section measurement, in order to have larger sensitivity to different Higgs production modes, the events selected in the mass region $118 < m_{4l} < 129$ GeV are split into exclusive categories. Such categories are based on the presence of additional leptons and the number of jets used to discriminate among the different production modes. Events are first categorised in a VH-leptonic category by requiring at least one additional isolated lepton with a transverse momentum greater than 8 GeV. Events not passing this requirement are categorised in exclusive categories according to the number of jets, 0, 1, 2 or more jets. In the 2-jet category, the events are further split into low ($m_{jj} < 120$ GeV) and high ($m_{jj} > 120$ GeV) dijet invariant mass. This division enables to further optimise the separation between the VH-hadronic (where the vector boson decays to a quark pair) and the VBF production Higgs boson productions. Dedicated Boosted Decision Tree (BDT) algorithms are used for the 0-jet and the 1-jet categories. For the 0-jet category, the BDT is trained on kinematic variables based on the 4-lepton final state to separate the gluon fusion process from the SM background. For the 1-jet category, the BDT is trained to disentangle gluon fusion production from VBF. For the 2-jet category, two BDTs are trained to separate the gluon fusion production from the VH hadronic and from the VBF mode and are used in the low and high mass categories.

1.2.3. Background modelling The main background component in the $H \rightarrow ZZ^* \rightarrow 4l$ final state is the non-resonant ZZ production. Additional background sources are the $Z+Jets$ and $t\bar{t}$ processes which are estimated in the signal region using different data-driven techniques according to the flavour of the sub-leading lepton pairs ($\mu\mu$ or $ee$). The $ll+\mu\mu$ component is estimated with the shape of the leading dilepton invariant mass in three control regions, defined by inverted selection requirements of the analysis, enriched in a different background component ($t\bar{t}$, $Z+heavy$ flavour, $Z+light$ flavour). The yield in the control region is extrapolated in the signal region using transfer factors. The $ll+ee$ background is mostly due to the mis-identification of light-flavour jets as electrons, photon conversions, and the semileptonic decays of heavy flavour hadrons. Similarly to the $ll+\mu\mu$ component, $ll+ee$ background yields are extracted in control regions and extrapolated in the signal region. A kinematic discriminant based on a BDT algorithm trained on input variables of the ZZ final state to disentangle the Higgs boson signal from the SM irreducible background is also employed. Figure 3 shows the mass spectrum for the leading dilepton pair, $m_{12}$, the sub-leading pair, $m_{34}$, the 4-lepton final state and the distributions of $m_{12}$ versus $m_{34}$ for data and signal and background Monte Carlo.

1.2.4. Results The measured total fiducial cross-section is $\sigma_{4l}^{fid}=4.48^{+1.01}_{-0.89}$ fb, in agreement with the SM expectations. Results on cross sections for different final states are also provided showing no tension with the SM predictions. The total cross section is obtained by extrapolating the fiducial cross section to the full phase-space and by taking into account the SM branching ratio $\mathcal{B}(H \rightarrow 4l)$, $\sigma_{\text{tot}}=81^{+18}_{-16}$ fb. The total measured cross section and the SM expectations are compatible within 1.5 standard deviations. The expected and observed yields in the various Higgs boson production categories (0-jet, 1-jet, 2-jet with $m_{jj} > 120$ GeV, 2-jet with $m_{jj} < 120$ GeV) are also extracted. The compatibility between the measured cross section for each production category and the SM predictions is at the level of 1.1 standard deviation. Figure 4 shows the observed and expected negative log-likelihood ratio scans for $\sigma_{ggF+ttH} \times \mathcal{B}(H \rightarrow ZZ^*)$, $\sigma_{VBF} \times \mathcal{B}(H \rightarrow ZZ^*)$ and $\sigma_{VH} \times \mathcal{B}(H \rightarrow ZZ^*)$ as well as the 2-dimensional compatibility checks among all the various production modes at 68% and 95% confidence level.
2. Higgs decay to fermions

2.1. VH(H→b̅b)

The process with the largest branching ratio (58%) for a SM Higgs boson of mass 125 GeV is H→b̅b. The overwhelming background produced from multi-jet at the LHC makes a fully inclusive search unfeasible. That is the reason why the production modes under study for this final state are the ones with W and Z bosons (VH) where the presence of leptons in the final state provides a clean signature and enables an efficient triggering of the event. Results have been presented with an integrated luminosity of 13.2 fb$^{-1}$ [4] from pp collision data collected in 2015 and 2016.

2.1.1. Object reconstruction, event categorisation and selection

Events are selected where two high transverse momentum b-tagged jets are reconstructed together with 0, 1 or 2 charged leptons (electrons or muons). A set of kinematic observables is used as input to a multivariate algorithm for each analysis category. This discriminant is then used for the extraction of the signal yield and the signal strength in the fit. Electrons and muons are identified and reconstructed as described in Section 1.2.1. Jets are reconstructed from energy clusters in the hadronic calorimeter...
Figure 4. Observed and expected negative log-likelihood scans for $\sigma_{ggF+ttH} \times B(H \rightarrow ZZ^*)$, $\sigma_{VBF} \times B(H \rightarrow ZZ^*)$ and $\sigma_{VH} \times B(H \rightarrow ZZ^*)$ with (black line) and without systematic uncertainties (red line). The expected SM negative log-likelihood scans are also shown. The green dashed lines indicate the value of the profile likelihood ratio corresponding to 1, 2 and 3 standard deviations for the parameter of interest. The plot on the bottom right side displays the negative log-likelihood contours at 68% and 95% confidence level in the $\sigma_{ggF+ttH} \times B(H \rightarrow ZZ^*)$-$\sigma_{VBF+VH} \times B(H \rightarrow ZZ^*)$. The SM prediction is represented by a dot in the 2-dimensional plane [3].

with the anti-$k_t$ algorithm with a radius parameter of 0.4. The raw energy of the reconstructed jets are calibrated using a jet energy scale correction extracted from a combination of data and Monte Carlo templates. The $b$-tagging algorithm is based on information of the jet kinematics, the properties of the tracks within a jet and the presence of displaced vertices in the event. Lepton-jet overlap removals are also applied to avoid double-counting of reconstructed particles in the final state.

Events passing detector quality requirements are split into categories according to their lepton, jet multiplicity and vector boson transverse momentum. In the 0-lepton channel, events are selected using the missing transverse energy trigger and additional selection requirements are applied on the angular separation between jets to further suppress multi-jet background. On the 1-lepton channel, events are selected with single electron trigger and are required to contain at
Figure 5. Invariant mass of the $b$-tagged jet pairs ($m_{bb}$) for the 0- and 1-lepton categories. The Higgs boson signal generated at $m_H=125$ GeV is shown as a filled histogram on top of the background components. The dashed histogram shows the total background as expected from the pre-fit Monte Carlo simulation. The size of the statistical and systematic uncertainty is indicated by hatched band around each bin. The ratio of the data to the sum of the signal and fitted background is also displayed [4].

least one lepton that is identified with tight criteria. In the 2-lepton selection, the same trigger requirement is applied as the one used in the 1-lepton category. Exactly two leptons identified with the loose criteria are required in the final state. Given that such leptons originate from the decay of the $Z$ boson, the invariant mass of the dilepton system must be between 71 and 112 GeV, around the $Z$ peak at 91 GeV.

The analysis strategy is based on a multivariate discriminant (BDT) trained in these three lepton categories for the 2- and 3-jet categories. For the 2-lepton channel, two BDTs are used depending on the transverse momentum of the vector boson. The discriminant is trained to separate the $VH \rightarrow b\bar{b}$ signal against the sum of all background processes. An additional BDT is also employed to separate the SM $VZ \rightarrow b\bar{b}$ signal production against the sum of all background processes in the event. The input variables of the BDT have been chosen to improve the signal-to-background separation; the most powerful being the mass of the di-jet system, $m_{bb}$ as shown in Figure 5.

The main background is the multi-jet production arising from QCD strong interactions at the LHC. This component contributes with very large cross section and is therefore the dominant challenge of the analysis. Background components are studied in the 0-, 1- and 2-lepton channels and specific strategies are carried out in the various categories. For instance, in the 1-lepton case, the background yields are extracted from control regions constructed separately for each of the 2- and 3-jet categories. Correction factors are then applied to extrapolate the yields and the shapes from the control region to the relevant signal region. In the 2-lepton region, requiring two isolated leptons with a dilepton invariant mass compatible with that of a $Z$ boson suppresses the contribution from multi-jet events. The residual contribution is found to be negligible (0.3%) and does not have impact on the signal extraction in the fit.

2.1.2. Results The results are extracted using a profile likelihood fit to measure the signal strength in the 8 BDT regions. For all channels combined, the expected value of the signal
The Higgs boson production associated with a pair of top quarks, $t\bar{t}H$, is very important for observing the top-Yukawa coupling of the Higgs boson to top quarks. Even though the $t\bar{t}H$ production is largely sub-dominant compared to the gluon fusion at the LHC, the presence of top quarks in the final state offers a very distinctive signature. One of the Higgs boson decay channels contributing with the largest branching ratio (58% for $m_H=125$ GeV) is that with two $b$-quarks in the final state. The analysis described in this Section is performed with 13.3 fb$^{-1}$ collected by the ATLAS experiment at $\sqrt{s}=13$ TeV [5] and focuses on the final state where the $W$ bosons from the top quarks decay leptonically to electrons or muons. This enables to trigger the event and strongly suppresses the overwhelming multi-jet background arising in the case of hadronic $W$ decays.

2.2. $t\bar{t}H(H\rightarrow b\bar{b})$

The Higgs boson production associated with a pair of top quarks, $t\bar{t}H$, is very important for observing the top-Yukawa coupling of the Higgs boson to top quarks. Even though the $t\bar{t}H$ production is largely sub-dominant compared to the gluon fusion at the LHC, the presence of top quarks in the final state offers a very distinctive signature. One of the Higgs boson decay channels contributing with the largest branching ratio (58% for $m_H=125$ GeV) is that with two $b$-quarks in the final state. The analysis described in this Section is performed with 13.3 fb$^{-1}$ collected by the ATLAS experiment at $\sqrt{s}=13$ TeV [5] and focuses on the final state where the $W$ bosons from the top quarks decay leptonically to electrons or muons. This enables to trigger the event and strongly suppresses the overwhelming multi-jet background arising in the case of hadronic $W$ decays.

2.2.1. Event selection and analysis strategy

Leptons and jets are identified and reconstructed as reported in Sections 1.2.1 and 2.1.1. Specific triggers are applied in the single lepton and dilepton channels. The events are classified in exclusive regions of jet and $b$-jet multiplicity in order to disentangle the signal component that is characterised by a large jet multiplicity with respect to the $t\bar{t}$ background. In the dilepton channel, the regions are five: the regions with (3 jets, 3 $b$-jets), (4 jets, 3 $b$-jets), (4 jets, 4 $b$-jets) are regarded as signal regions. In the single lepton case, the categorisation is exploited in nine categories, being the signal regions the ones with (5 jets, 4 $b$-jets), (6 jets, 3 $b$-jets) and (6 jets, 4 $b$-jets). The dominant background is $t\bar{t}$ with additional heavy flavours jets (tt$b\bar{b}$, t$t\bar{c}\bar{c}$) as shown in Figure 7.

In the signal regions two boosted decision trees (BDT) are employed. The first BDT (reconstruction BDT) is trained to match the reconstructed jets to the partons from the top and Higgs decays. In each signal region, the information from the output of the reconstruction BDT is used with other kinematic variables into another multivariate algorithm (classification BDT) which separates events as being more signal- or background-like. The shapes of the classification BDT in the signal regions are used as inputs to the final fit to data. Similarly in the dilepton (3j, 3b) region, a neural network (NN) is applied to disentangle signal from background. In the control regions of the single lepton channel, the scalar sum of the transverse momentum of all
2.2.2. Signal and background modelling

The $t\bar{t}H$ production is treated with NLO simulation for the matrix element calculation interfaced to the Pythia 8 program for what concerns parton shower and hadronisation. The dominant $t\bar{t}$ background is categorised according to the flavour of the additional jets in the event. To model such component with the best possible precision and to ensure consistent data-Monte Carlo comparisons, detailed studies on the parton shower schemes applied and sequential reweightings to higher-order Monte Carlo generations are performed. Other backgrounds are represented by $Wt$, $W/Z$ + jets and are sub-dominant. In the single-lepton channel, an additional source of background is due to events with a misidentified or non-prompt leptons. This component is estimated in data.

2.2.3. Results

The main source of systematic uncertainty affecting the measurement of the parameter of interest $\mu$ is the modelling of the $t\bar{t}$ background. An uncertainty of 6% is assumed for the inclusive $t\bar{t}$ cross section computed at NNLO+NNLL including the effects from the variation of the factorisation, resummation scales and the parton density functions. An additional uncertainty on the choice of the Monte Carlo generator, the showering and the hadronisation models is also applied. The statistical analysis is based on a likelihood function formed as a product of Poisson probability for each bin of the input distributions in the various signal and control regions. The parameter of interest of the fit is the Higgs boson signal strength, $\mu$, being $\theta$ the set of nuisance parameters carrying the effects of the systematic uncertainties. These nuisance parameters are treated with Gaussian or log-normal priors and are correlated across all the regions and channels. The $t\bar{t}b\bar{b}$ normalisation is left free floating and its value is extracted by the fit. As shown in Figure 8, the distribution of the BDT discriminant in the signal region (6j, 4b) after the fit exhibits a good data-Monte Carlo agreement given that the $t\bar{t}b\bar{b}$ and $tt\bar{c}\bar{c}$ components are scaled by approximately 1.30 times the pre-fit value. As reported in Figure 8, the observed signal strength is $4.6^{+2.0}_{-1.7}$ in the dilepton data, $1.6^{+1.3}_{-1.1}$ in the single-lepton final state. The combined value is $2.1^{+1.0}_{-0.9}$. The error on the measurement is mostly dominated by the systematic uncertainty on the background modelling.
Figure 8. Post-fit comparison between data and prediction for the BDT discriminant in the single-lepton channel signal region (6j, 4b). The signal $t\bar{t}H$ signal is normalized to the fitted signal strength $\mu$ extracted by the fit. The dashed line show the $t\bar{t}H$ distribution normalized to the total yield. The hatched line correspond to the total uncertainty on the normalisation of the Monte Carlo predictions. Signal strength measurements on the right-side distribution in the individual channels and for the combination [5].

2.3. $t\bar{t}H$ in multilepton final states

This Section focuses on the search of the $t\bar{t}H$ Higgs production using 13.2 fb$^{-1}$ of data collected with the ATLAS detector at $\sqrt{s}=13$ TeV during 2015 and 2016 [6]. The search uses four final states distinguished by the number and flavour of leptons: two same-charge light leptons (electrons or muons) and no hadronically decaying $\tau$ leptons, two same-charge light leptons and one hadronically decay $\tau$ lepton, three light leptons and four light leptons. Based on the number of lepton candidates after the preselection requirements, events are placed into at most one of these categories. Additional requirements beyond the preselection classification are applied depending on the final state. Such categorisation is mostly sensitive to $H \rightarrow WW^*$ (mainly in the 0-$\tau$ channel) and $H \rightarrow \tau\tau$ (in the 1-$\tau$ channel).

Backgrounds are categorised into those in which all the selected leptons are produced in decays of electroweak bosons or $\tau$ leptons (prompt leptons) and those in which at least one lepton arises from another source. In such cases, the leptons arise from hadronic decay channels or photon conversions (non-prompt leptons), interactions in detector material (charge mis-identification) or wrong reconstruction of other particles (fake leptons). Signal-free control regions are defined with inverted selection requirements for each channel of the analysis. For each control region, the background yield is extracted and extrapolated in the signal region with transfer factors. The expected backgrounds, the $t\bar{t}H$ signal and the observed data yields in each category of the analysis are shown in Figure 9. The best fit value of the signal strength is extracted with a maximum likelihood approach on the six categories which are treated with Poissonian terms in the likelihood parametrisation. Systematic uncertainties are implemented as nuisance parameters with priors which the fit is able to constrain. The best fit value of the $t\bar{t}H$ signal strength combining all channels is $\mu=2.5\pm0.7$ (stat) $\pm1.0$ (sys) as shown in Figure 9. The observed $p$-value associated with the background-only hypothesis is 2.2 standard deviations for $m_H=125$ GeV.

\[\text{Data} / \text{Pred.}\]

\[\text{Events}\]

\[\text{ATLAS Preliminary}\]

\[\begin{array}{c}
\text{Total} \\
\text{Stat.} \\
\text{Tot. (Stat. Syst.)}
\end{array}\]

\[\begin{array}{c}
\text{Dilepton} \\
\text{Single Lepton} \\
\text{Combined}
\end{array}\]

\[\begin{array}{c}
\text{4.6} \\
\text{1.6} \\
\text{2.1}
\end{array}\]

\[\begin{array}{c}
+2.9 \quad +1.4 \quad +2.6 \\
-2.3 \quad -1.3 \quad -1.9 \\
+1.1 \quad +0.5 \quad +1.0 \\
-1.1 \quad -0.5 \quad -0.9 \\
+1.0 \quad +0.5 \quad +0.9 \\
-1.0 \quad -0.5 \quad -0.7
\end{array}\]
2.4. Combination of the $t\bar{t}H$ analyses

The following decay modes are considered for the $t\bar{t}H$ combination [7]:

- $H \rightarrow \gamma\gamma$ in both the hadronic and leptonic $t\bar{t}$ decay channels (Section 1.1);
- $H \rightarrow WW^*, \tau\tau, ZZ$ (Section 2.3);
- $H \rightarrow b\bar{b}$ in the single lepton and opposite sign dilepton $t\bar{t}$ decay channels (Section 2.2).

The orthogonality among the various analyses is ensured by using a common lepton definition for the categorisation of the channels in $H \rightarrow WW^*, \tau\tau, ZZ^* \rightarrow$ leptons and $H \rightarrow b\bar{b}$ analyses. The combination is performed with the full dataset of $pp$ collisions at $\sqrt{s} = 13$ TeV corresponding to an integrated luminosity of $13.3 \text{ fb}^{-1}$. The distributions of the discriminant from each of the channels considered are combined to test for the presence of a signal assuming a Higgs boson mass of $m_H = 125$ GeV. The statistical analysis is based on a binned likelihood function defined as the product of Poisson probability components over all bins considered in the analysis. The parameter of interest is the signal-strength $\mu$ and the nuisance parameters denote the set of continuous values that describe the effect of each systematic uncertainty on the signal and background expectations in each region. Such nuisance parameters adjust the expectations for signal and background according to the corresponding systematic uncertainties. The test statistics employed is the profile likelihood ratio and a correlation scheme is defined to treat coherently the nuisance parameters coming from different final states.

Figure 10 summarises the observed fitted signal strength of the individual channels and the combination. The best fit value is found to be: $\mu_{t\bar{t}H} = 1.8 \pm 0.7$ and the compatibility of the individual signal strengths per channels with the combination is $7\%$. The likelihood profile for individual channels and for the combination is reported in Figure 10. The largest systematic uncertainty contributing to the measurement is the non-resonant $t\bar{t}$ background modelling affecting the $H \rightarrow b\bar{b}$ final state. The combined expected (observed) significance of the Higgs boson signal in the $t\bar{t}H$ production mode is $2.8 (1.8)$ standard deviations.

2.5. $H \rightarrow \mu\mu$

The $H \rightarrow \mu\mu$ decay is a sensitive channel in which the Higgs coupling to second-generation fermions can be measured at the LHC with a clean signature in the final state. Given its
Figure 10. Observed signal strength, $\mu_{t\bar{t}H}$, measurements from the individual analyses and for their combination assuming $m_H=125$ GeV. The total, statistical and systematic uncertainties on $\mu_{t\bar{t}H}$ are shown. The SM expectation for $\mu_{t\bar{t}H}$ ($\mu_{t\bar{t}H}=1$) is shown as the black vertical line. The signal strength extracted for the Run 1 combination is also reported for comparison. Negative logarithmic likelihood ratio as a function of the signal strength for the various channels and for the combination, assuming $m_H=125$ GeV. The horizontal dashed lines correspond to 1, 2 and 3 standard deviations [7].

very small branching ratio, $\mathcal{B}(H \rightarrow \mu\mu)=2.18 \cdot 10^{-4}$, this process is very hard to observe at the LHC though. The search described in this Section is performed using data corresponding to an integrated luminosity of 13.2 fb$^{-1}$ in $pp$ collisions collected with the ATLAS detector [8].

2.5.1. Object definition and event selection  
Muons and electrons are identified according to the criteria described in Section 1.2.1. Light jets and jets containing $b$-hadrons are identified and reconstructed as reported in Section 2.1.1.

Events are required to have at least one primary vertex that has two associated tracks. If there is more than one vertex reconstructed in the event, the one with the largest squared track transverse momentum is chosen to be the primary vertex. Di-muon events are selected by requiring two opposite-charge muons with additional cuts on the transverse momentum on the leading and sub-leading muons. To improve data-Monte Carlo agreement for the muon transverse momentum, a reweighting method is adopted to correct the distribution of the $p_T^{\mu\mu}$ from $Z+jets$ MC to match the data.

In order to increase the sensitivity of the search, the selected events are split into seven categories with different signal-to-background ratios. These categories are created on the muon pseudorapidity, $p_T^{\mu\mu}$ and VBF di-jet signatures. The latter is characterised by two forward jets with very large rapidity gap and little hadronic activity between them. The usage of a BDT discriminant is employed to define this VBF signal region.

2.5.2. Signal and background modelling  
The signal models for the gluon fusion and the VBF production mechanisms are obtained from simulated Higgs boson samples. This model is defined as the sum of a Crystal Ball function and a Gaussian core. The background is treated with a fit using the convolution of a Breit-Wigner function with a gaussian and an exponential distributions.
Figure 11. Background model fit to the $m_{\gamma\gamma}$ distribution in data for the low $p_T^{\mu\mu}$ category for the central pseudorapidity region. Statistical uncertainties are indicated on the data points. The expected signal is shown for $m_H=125$ GeV and is scaled by a factor 20. Observed and expected 95% upper limit on the $\sigma \times B(H \to \mu\mu)$ as a function of $m_H$ over the range 115-145 GeV. The dark- and light-shaded regions denote the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainty bands on the expected limit [8].

In order to derive results, a binned maximum likelihood fit to the observed $m_{\mu\mu}$ distributions in the range 110-160 GeV is performed using the sum of the signal and background models. The fit is employed simultaneously in all seven categories. The $m_{\mu\mu}$ spectra for data and for the signal/background parametrisations is shown in Figure 11 for the low $p_T^{\mu\mu}$ in the central pseudorapidity region. Upper limits on $\sigma \times B(H \to \mu\mu)$ are displayed in Figure 11. For the Higgs mass of 125.09 GeV, the observed (expected) upper limit on the signal strength at 95% confidence level is 4.4 (5.5) times the SM prediction.

3. Conclusions
Following the Higgs boson discovery in 2012 in the $H \to \gamma\gamma$, $H \to ZZ^* \to 4l$ and $H \to WW^*$ and the measurement of its properties in the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$ final states with the final LHC Run 1 dataset, recent years (2015 and 2016) have seen a focus on re-discovery of the Standard Model Higgs boson and the extraction of its properties in the bosonic channels (Section 1) together with the search of this particle in the fermionic final states (Section 2). Measurements collected so far with approximately 15 fb$^{-1}$ of $pp$ collisions at the ATLAS experiment are consistent with the SM predictions within uncertainties.

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