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Measurements of the Higgs production cross section in the $H \to \tau\tau$ decay channel with the ATLAS experiment

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Measurements of the Higgs production cross section in the $H \to \tau\tau$ decay channel are presented. The results are obtained using 36.1 fb^{-1} of data collected by the ATLAS experiment at $\sqrt{s} =$ 13 TeV. The observed (expected) significance of the $H \to \tau\tau$ signal excess over the expected background amounts to 4.4 (4.1) standard deviations. This result, combined with the data taken at $\sqrt{s} = 7$ and 8 TeV, leads to an observed (expected) significance of 6.4 (5.4) and constitutes the first ATLAS observation of $H \to \tau\tau$. The measured total cross section of $H \to \tau\tau$, using the data collected at $\sqrt{s} = 13$ TeV, is $3.77^{+0.60}_{-0.59}$ (stat.) $^{+0.87}_{-0.74}$ (syst.) pb, assuming the relative contributions of the Higgs production processes as predicted by the Standard Model. In addition, measurements of the vector boson fusion and gluon-gluon fusion have been performed separately and similar results are reported based on the simplified template cross section framework. All the measurements are in agreement with the Standard Model predictions.

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1. Introduction

A particle compatible with the Standard Model (SM) Higgs boson was discovered by the ATLAS and CMS experiments in 2012 [1, 2]. After the Higgs boson discovery, the studies have been focused on measuring its properties such as coupling strengths, spin and CP quantum numbers. Several measurements have been performed during Run 1 of the LHC at a center of mass energy of $\sqrt{s} = 7$ and 8 TeV and they have not shown any deviation from the SM predictions. Only the Higgs couplings to the third generation fermions are currently accessible at the LHC. The $H \to \tau\tau$ decay channel is considerably important since it allows to direcly measure the Higgs Yukawa coupling in the leptonic decay mode (limits have been set to the $H \to \mu\mu$ but there is not an evidence yet). The observation of $H \to \tau\tau$ decay has already been established by the ATLAS and CMS combined measurement using Run 1 data with a significance of 5.5σ [3]. Nevertheless the $H \to \tau\tau$ can benefit from the higher Run 2 statistics in order to reach higher precision results.
The analysis [4], presented in this article, has been performed using the 2015 and 2016 data recorded by the ATLAS detector [5] at the LHC, corresponding to an integrated luminoisity of 36.1 fb^{-1}. All combinations of possible decay modes have been exploited in the analysis: both leptonic ($\tau \to l\nu\bar{\nu}$ with $l = e, \mu$) and hadronic ($\tau \to$ hadrons ν) τ decays. The three decay channels will henceforth be referred to as $\tau_{\text{lep}}\tau_{\text{lep}}$, $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$.

2. Event selection

The analysis aims at measuring the Higgs boson production cross section exploiting signal sensitive event topologies. Therefore, two kinds of signal regions (SRs) are defined: one region called "VBF" which targets events produced through vector boson fusion (VBF) and a region called "boosted" which targets events produced through gluon-gluon fusion (ggF) with an additional recoiling jet. These two kinds of SRs are defined applying some kinematical requirements (after having selected the physics objects and applied some preselection cuts). The VBF is characterized by two high-p_{T} jets which are required to have a large pseudorapidity gap ($|\Delta\eta_{jj}| > 3$) and large invariant mass ($m_{jj} > 400$ GeV). The boosted category contains instead events that fail the VBF selection and are characterized by an high-p_{T} Higgs boson ($p_{\text{T}}^{\text{H}} > 100$ GeV). In the analysis the SRs are further split into subregions in order to increase the sensitivity, for a total of thirteen SRs. Figure 1 shows the $m_{\tau\tau}^{\text{MMC}}$ distributions for the sum of all VBF (a) and the sum of all boosted (b) regions, where the $m_{\tau\tau}^{\text{MMC}}$ is the Higgs invariant mass obtained with the Missing Mass Calculator (MMC) [6] algorithm.

In addition, six control regions (CRs) are used to constrain the $Z \to ll$ and the top-quark backgrounds and one validation region (VR) is used to verify the correct modelling of the $Z \to \tau\tau$ background, as will be illustrated in Section 3.

3. Backgrounds estimation

The different final states of the three decay channels imply different background compositions and also need different strategies for background estimation.
The Drell-Yan process $Z/\gamma^* \to \tau\tau$ constitutes the main irreducible background. In addition, the

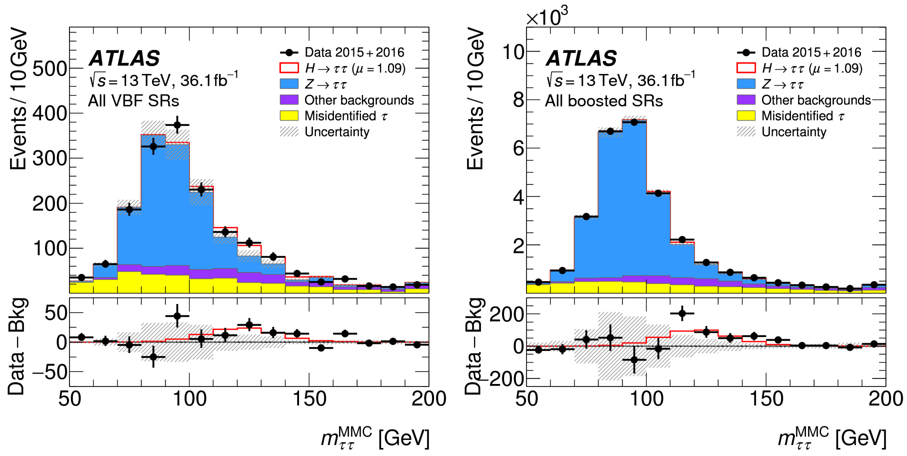

Figure 1: $m_{\tau\tau}^{\text{MMC}}$ distributions for the sum of all VBF (a) and all boosted (b) signal regions. The bottom panel shows the difference between observed data and expected background [4].

separation between $Z \rightarrow \tau\tau$ and $H \rightarrow \tau\tau$ is limited by the $m_{\tau\tau}^{\text{MMC}}$ resolution. This background is estimated using simulations, namely using SHERPA [7] Monte Carlo generator at Next-To-Leading Order (NLO). The normalization of this major background is directly retrieved from the fit to data and no specific control region is defined. Therefore, in order to verify the correctness of the $Z \rightarrow \tau\tau$ background modeling, a validation region is used instead. Since it is difficult to select a pure $Z \rightarrow \tau\tau$ sample, this region is built using a selection based on the $\tau_{\text{lep}}\tau_{\text{lep}}$ SR and using $Z \rightarrow ll$ events.

The $Z \rightarrow ll$ and top-quark backgrounds are significant backgrounds for the $\tau_{\text{lep}}\tau_{\text{lep}}$ and $\tau_{\text{lep}}\tau_{\text{lep}}$, $\tau_{\text{lep}}\tau_{\text{had}}$ channels respectively. The top-quark background refers to the production of $t\bar{t}$ pairs or to single top quarks. They are both estimated using simulations and CRs are defined in order to constrain their normalization. A $Z \rightarrow ll$ CR in the $\tau_{\text{lep}}\tau_{\text{lep}}$ channel is used and defined requiring the m_{ll} to be $80 < m_{ll} < 100$ GeV. Top CRs for both the $\tau_{\text{lep}}\tau_{\text{lep}}$ and $\tau_{\text{lep}}\tau_{\text{had}}$ channels are used and defined inverting the b-jet veto requirement (in the $\tau_{\text{lep}}\tau_{\text{lep}}$ and $\tau_{\text{lep}}\tau_{\text{had}}$ selections, it is required not to contain b-tagged jets).

Another significant background arises from hadronic jets which are misidentified as τ_{had} or as electrons or muons. In order to estimate this background different data-driven techniques are used in the three decay channels. The main sources of this background are QCD jets and W/Z produced in association with jets. In the case of $\tau_{\text{lep}}\tau_{\text{lep}}$ channel, templates are built in dedicated control regions and the normalization is retrieved from extrapolation to the signal region. The $\tau_{\text{lep}}\tau_{\text{had}}$ channel uses a method called "fake-factor" where the fraction of misidentified events is derived in dedicated control regions and propagated to the signal region. The normalisation is derived from control region extrapolation. The $\tau_{\text{had}}\tau_{\text{had}}$ channel uses templates built in a dedicated control region and the normalization is directly retrieved from the fit to data.

4. Statistical analysis

A maximum likelihood fit is performed on data in order to extract the parameter of interest, namely the $\sigma_{H\to\tau\tau}$ total cross section. A fit model is constructed using the $m_{\tau\tau}^{\mathrm{MMC}}$ distributions in the SRs and only the event yields in the CRs. SRs are modeled by a product of Poisson distributions, each of this distribution representing the event yield in intervals of $m_{\tau\tau}^{\mathrm{MMC}}$ while CRs are modeled by a single Poisson distribution that describes the event count in that region. Systematic uncertainties are also taken into account as nuisance parameters and parametrized by Gaussian or log-normal distributions. Both theoretical and experimental uncertainties are considered. A summary of the different sources of uncertainty and their impact on $\sigma_{H\to\tau\tau}$ is given in Table 1.

Source of uncertainty	Impact $\Delta\sigma/\sigma_{H\to\tau\tau}$ [%] Observed	Expected
Theoretical uncert. in signal	+13.4 / −8.7	+12.0 / −7.8
Background statistics	+10.8 / −9.9	+10.1 / −9.7
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	+11.2 / −9.1	+10.4 / −8.4
Background normalization	+6.3 / −4.4	+6.3 / −4.4
Misidentified τ	+4.5 / −4.2	+3.4 / −3.2
Theoretical uncert. in background	+4.6 / −3.6	+5.0 / −4.0
Hadronic τ decays	+4.4 / −2.9	+5.5 / −4.0
Flavor tagging	+3.4 / −3.4	+3.0 / −2.3
Luminosity	+3.3 / −2.4	+3.1 / −2.2
Electrons and muons	+1.2 / −0.9	+1.1 / −0.8
Total systematic uncert.	+23 / −20	+22 / −19
Data statistics	±16	±15
Total	+28 / −25	+27 / −24

Table 1: Systematic uncertainties grouped in categories. The impact on $\sigma_{H\to\tau\tau}$ is shown [4].

5. Results

The measured value of $\sigma_{H\to\tau\tau}$ is $3.77^{+0.60}_{-0.59}$ (stat.) $^{+0.87}_{-0.74}$ (syst.) pb where all the relative contributions of the Higgs prodcution processes are assumed to be as predicted by the SM. This value is compatible with the SM prediction which is $\sigma_{H\to\tau\tau}^{\mathrm{SM}} = 3.46 \pm 0.13$ pb (Figure 2 (a)). In addition, since the VBF and boosted categories are sensitive to the VBF and ggF production mechanism respectively, a two parameter fit has also been performed to determine the cross sections of these production processes. The resulted values are $\sigma_{H\to\tau\tau}^{\mathrm{VBF}} = 0.28 \pm 0.09$ (stat.) $^{+0.11}_{-0.09}$ (syst.) pb and $\sigma_{H\to\tau\tau}^{gg\mathrm{F}} = 3.1 \pm 1.0$ (stat.) $^{+1.6}_{-1.3}$ (syst.) pb. Both cross sections values are in agreement with the SM predictions (Figure 2 (b)).

In addition, a first attempt to measure ggF and VBF cross sections using selections based on the simplified template cross section framework has been performed. Table 2 shows the results using a three parameters fit.

The observed (expected) significance of the signal excess relative to the background-only hypothesis is 4.4 (4.1) standard deviations. This result, combined with the Run 1 result [8] obtained using data collected at 7 and 8 TeV center of mass energies, leads to an observed (expected) significance of 6.4 (5.4) standard deviations. This constitutes the first ATLAS observation of the $H \to \tau\tau$ decay.

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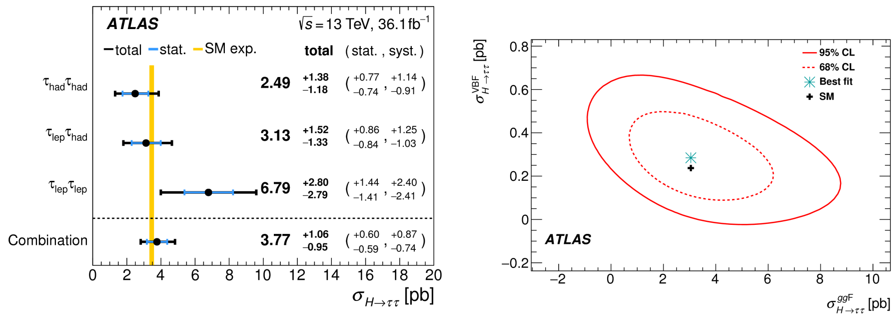

(a) (b)

Figure 2: $\sigma_{H\to\tau\tau}$ measurement in the various subchannels and for the combined result. The predicted value from the SM with its uncertainty is shown in yellow (a). 95% and 68% C.L. contours in the plane of $\sigma^{VBF}_{H\to\tau\tau}$, $\sigma^{ggF}_{H\to\tau\tau}$ (b). The value predicted by the SM is indicated by the black point while the best-fit value is shown as a star [4].

Process	Particle-level selection	σ [pb]	σ^{SM} [pb]
ggF	$N_{jets} \geq 1$, $60 < p_T^H < 120$ GeV, $\lvert y_H\rvert < 2.5$	1.79 ± 0.53 (stat.) ± 0.74 (syst.)	0.40 ± 0.05
ggF	$N_{jets} \geq 1$, $p_T^H > 120$ GeV, $\lvert y_H\rvert < 2.5$	0.12 ± 0.05 (stat.) ± 0.05 (syst.)	0.14 ± 0.03
VBF	$\lvert y_H\rvert < 2.5$	0.25 ± 0.08 (stat.) ± 0.08 (syst.)	0.22 ± 0.01

Table 2: VBF and ggF cross section measurements in three exclusive regions. The definitions are based on the simplified template cross section framework [4].

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