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Study of the $H \to \tau\tau$ channel with ATLAS

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After the discovery of the Higgs boson, the precision measurements of its properties and the comparison with the Standard Model (SM) predictions became the crucial part of the Large Hadron Collider (LHC) physics programme. A potential observation of deviations from the SM predictions may lead to the discovery of a new physics. The direct observation of the coupling of the Higgs boson to leptons and its measurements is of particular importance. The status of the Higgs boson measurements in the $\tau\tau$ decay mode with the ATLAS experiment is presented; the measurements are performed using pp collision data from the LHC with full Run 1 dataset.

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1. Introduction

The experimental confirmation of the Brout-Englert-Higgs mechanism, and more generally the investigation of the electroweak symmetry breaking origin, was one of the main goals of the physics programme at the Large Hadron Collider (LHC) at CERN. With the discovery of a new particle with a mass of 125 GeV by the ATLAS [1][2] and CMS collaborations [3], this goal was achieved. The new particle was observed in decays to a pair of bosons, $\gamma\gamma$, ZZ and WW, and further studies confirmed the observed particle's properties are consistent with the SM predictions for a Higgs boson with mass $m_H = 125$ GeV. Besides the bosonic decay modes, the SM predicts that the Higgs boson decays to fermions as well. Moreover, the mass generation mechanism for fermions, as implemented in the SM, can only be established by measuring the direct coupling of the Higgs boson to fermions.

The fermionic decays with the highest branching ratios are decays to a pair of b-quarks, $H \to bb$ and to a pair of τ leptons, $H \to \tau\tau$, since the Yukawa couplings of the Higgs boson to fermions are proportional to fermions' masses. However, the search for $H \to bb$ decays is challenging due to the presence of high irreducible QCD background; thus, the most promising candidate to measure the Higgs boson coupling to fermions is $H \to \tau\tau$, given the good signal-to-background ratio.

At the LHC, the main Higgs production modes are the gluon fusion production mode (ggF) via a heavy quark loop, in the vector boson fusion mode (VBF) and the association with a vector boson (VH).

In this document the measurement of $H \to \tau\tau$ decay is presented. This measurement is performed using 24.8 fb^{-1} of pp collision data at $\sqrt{s} = 7$ and 8 TeV collected by the ATLAS experiment in 2011 and 2012 [4]. All decays of the τ lepton (both leptonic τ_{lep} and hadronic τ_{had}) are considered, leading to three analysis channels denoted $\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$. The analysis is based on a Boosted Decision Tree (BDT) classification to separate backgrounds from the signal. As a cross-check, separate analysis has been performed applying cuts on kinematic variables.

2. $H \to \tau\tau$ measurement

The $H \to \tau\tau$ decay is the most sensitive channel among the leptonic Higgs boson decays, due to its high branching ratio. Following a preselection, detailed in Ref. [4], events in each di-tau final state are split into two categories. The VBF category contains events with two jets emitted back-to-back in the forward part of the detector and targets the signal events produced through the VBF production. The "Boosted" category targets the signal events in which the Higgs boson has been produced with high transverse momentum, primarily from the ggF production. Combining the analysis channels and categories yields six signal regions. Separate BDTs are trained for each region, using between six and nine input variables. The selection of these variables has been separately optimized for each signal region, in order to exploit discriminating features such as resonance properties, event activity and topology, as well as the characteristic VBF topology in the corresponding category. One of the most important input variables is the mass of the di-tau system, whose reconstruction is quite challenging due to the presence of at least two neutrinos in the final state; the Missing Mass Calculator (MMC) is used for this purpose [5]. On the left, Fig. 1 shows a

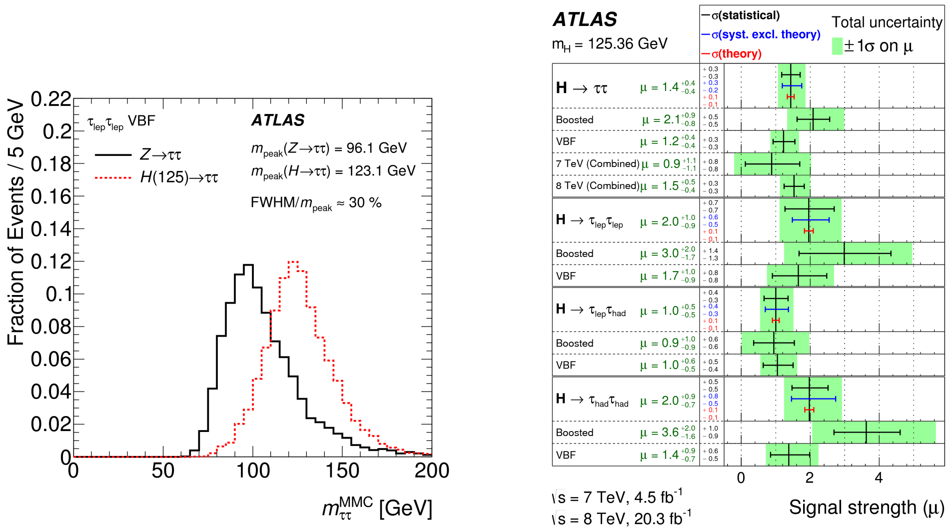

Figure 1: Left: The reconstructed invariant $\tau\tau$ mass, $m_{\tau\tau}^{MMC}$ for $H \to \tau\tau$ and $Z \to \tau\tau$ events in MC simulation and embedding respectively, for the events passing the boosted category selection in $\tau_{lep}\tau_{had}$ channel [4]. Right: The best-fit value for the signal strength μ in the individual channels and their combination for the full ATLAS datasets at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV. The total $\pm 1\sigma$ uncertainty is indicated by the shaded green band, with the individual contributions from the statistical uncertainty (top,black), the experimental systematic uncertainty (middle, blue), and the theory uncertainty (bottom, red) on the signal cross section (from QCD scale, PDF, and branching ratios). The corresponding uncertainity values are shown in the central column [4].

comparison of the reconstructed masses for the data-based estimate of $Z \to \tau\tau$ (see next paragraph) and signal Monte Carlo in the $\tau_{lep}\tau_{had}$ channel. Good discrimination is observed.

The background composition differs between each analysis channel, but in all channels, the most important background is the irreducible $Z \to \tau\tau$ production. This background is modeled using the embedding technique, which selects the $Z \to \mu\mu$ events in data and replaces the reconstructed muons by simulated τ lepton decays. Thus, the Z boson kinematics and all other event activity comes entirely from data. Another important background in $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ channels stems from jets being misidentified as hadronic τ leptons. Fully data-driven techniques are used to estimate these backgrounds from misidentified τ decay products, described in detail in Ref. [4]. In addition, control regions are introduced to normalize the background contributions from top-quark production and $Z \to \ell\ell$ production. The signal strength is extracted by fitting the BDT score with signal and background templates simultaneously in the six signal regions together with nine control regions to better constrain the background normalizations. An excess of data events over the background prediction is observed in all the three analysis channels.

The observed (expected) significance of the measurement is 4.5 σ (3.4 σ) providing direct evidence for $H \to \tau\tau$ decays. On the right, Fig. 1 shows the observed value of μ in the individual channels. The measured signal strength for a Higgs boson mass of 125 GeV is

$$\mu = 1.43^{+0.27}_{-0.26}(\text{stat.})^{+0.32}_{-0.25}(\text{syst.}) \pm 0.09(\text{theo.}).$$

The distribution of the invariant mass for the pair of τ leptons peaks around the measured Higgs mass value, as it can be seen in Fig. 2 left. Distributions of the BDT discriminants for the

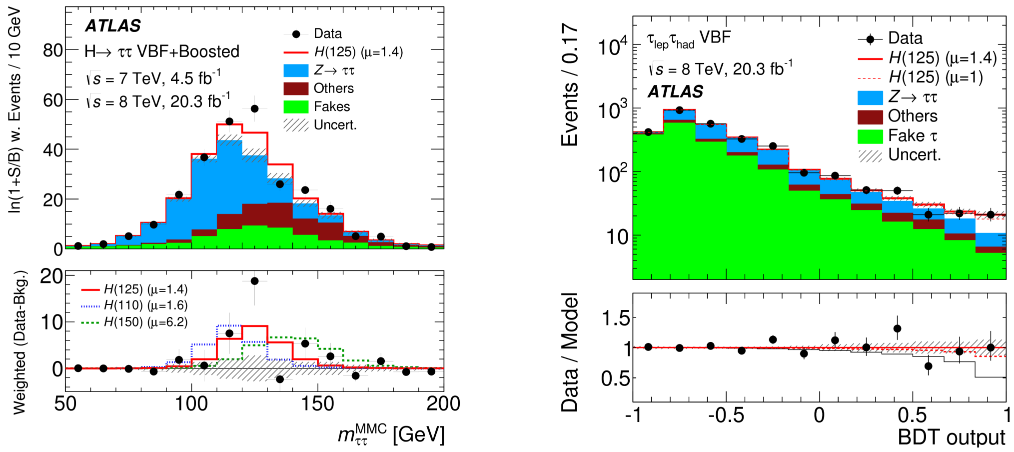

Figure 2: Left: Distributions of the reconstructed invariant $\tau\tau$ mass, $m_{\tau\tau}^{MMC}$, with events weighted by $\ln(1+S/B)$ for all channels. These weights are determined by the signal (S) and background (B) predictions for each BDT bin. The bottom panel in each plot shows the difference between the weighted data events and weighted background events (black points), compared to the weighted signal yields. The background predictions are obtained from the global fit with the $m_H = 125$ GeV signal hypothesis (signal strength = 1.4). The $m_H = 125$ GeV signal is plotted with a solid red line, and, for comparison, signals for $m_H = 110$ GeV (blue) and $m_H = 150$ GeV (green) are also shown. The signal normalizations are taken from fits to data. with the corresponding signal mass hypotheses, and the fitted μ values are reported in the figure. Right: Distributions of the BDT discriminants for the data taken at $\sqrt{s} = 8$ TeV in the VBF signal region category for $\tau_{lep}\tau_{had}$ channel. The Higgs boson signal ($m_H = 125$ GeV) is shown stacked with a signal strength of $\mu = 1$ (dashed line) and $\mu = 1.4$ (solid line). The background predictions are determined in the global fit (that gives $\mu = 1.4$). The size of the statistical and systematic normalization uncertainties is indicated by the hashed band. The ratios of the data to the model (background plus Higgs boson contributions with $\mu = 1.4$) are shown in the lower panels. The dashed red and the solid black lines represent the changes in the model when $\mu = 1.0$ or $\mu = 0$ are assumed respectively. Taken from Ref. [4].

data taken at $\sqrt{s} = 8$ TeV in the signal regions of the VBF category for $\tau_{lep}\tau_{had}$ channel is shown in Fig. 2 right.

The leading systematic uncertainties on the measurement are the theoretical systematic uncertainty on the ggF production, the uncertainty on the normalization of the $Z \to \ell\ell$ and top quark backgrounds in $\tau_{lep}\tau_{had}$, and the uncertainty on the jet energy scale calibration.

The search for the SM Higgs boson presented above has been cross-checked for the dataset collected at $\sqrt{s} = 8$ TeV performing an analysis with cuts applied on kinematic variables. To allow a straight-forward comparison of the results, the multivariate and cut-based analyses have common components. In particular, they are performed for the same three channels, they use the same preselection and share the same strategy for the estimation of background contributions and systematic uncertainties. There is a good agreement between the results of the two analyses for the individual channels as well as for their combination.

3. Conclusions

A review of the results of the measurement of the Higgs boson decays to a pair of τ leptons has been presented and evidence of this decay mode has been established. The measured signal strength $\mu = 1.43^{+0.27}_{-0.26}(\text{stat.})^{+0.32}_{-0.25}(\text{syst.}) \pm 0.09(\text{theo.})$ is in agreement with the SM prediction. This measurement is performed using pp collision data from the LHC at $\sqrt{s} = 7$ and 8 TeV collected by the ATLAS experiment in 2011 and 2012.

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