PROCEEDINGS OF SCIENCE

Experimental results using the decay of the Higgs boson to tau leptons and muons

Mareike Meyer* **on behalf of the ATLAS and CMS Collaborations**
DESY, Notkestr. 85, 22607 Hamburg, Germany
E-mail: mareike.meyer@desy.de

Precise measurements of the Higgs boson Yukawa couplings provide important tests of the Standard Model of particle physics. This review summarizes the current status of the analyses performed by the ATLAS and CMS experiments that search for the Higgs boson decay into a pair of muons. Additionally, two measurements in the Higgs boson decay channel into a pair of tau leptons are presented. The first analysis discussed was performed by the ATLAS collaboration and targets Higgs bosons produced via vector boson fusion and gluon fusion. The second presented analysis is a search performed by the CMS collaboration targeting Higgs bosons produced in association with a vector boson.

Sixth Annual Conference on Large Hadron Collider Physics (LHCP2018)
4-9 June 2018
Bologna, Italy

*Speaker.

PoS(LHCP2018)152

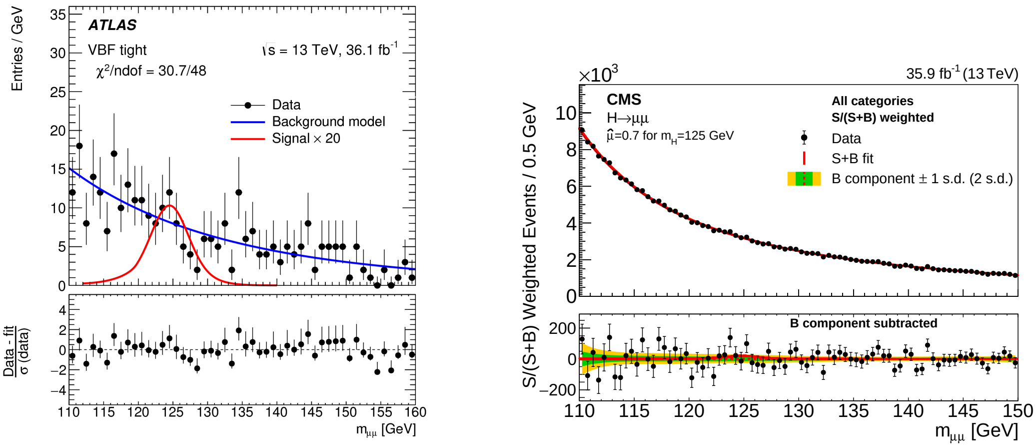
1. Introduction

Since the discovery of the Higgs boson in 2012 [1–3] one of the primary goals of the ATLAS [4] and CMS [5] experiments at the LHC has been studying the properties of the newly discovered particle. While precise measurements of the mass and other properties of the Higgs boson still predominantly rely on analyses in the bosonic decay channels of the Higgs boson [6–8], establishing the couplings of the Higgs boson to fermions and precise measurements of these Higgs boson Yukawa couplings provide important tests of the Standard Model of particle physics.
Measurements of the Higgs boson Yukawa couplings have so far been performed in the Higgs boson decay channel into a pair of bottom quarks, a pair of tau leptons and a pair of muons by the ATLAS and CMS experiments. The top quark Yukawa coupling is studied by both experiments in events where the Higgs boson is produced in association with a top quark pair. Recently, Higgs boson production in association with a top quark pair and Higgs boson decays into a pair of bottom quarks have been observed by both the ATLAS and the CMS collaboration [9–12]. The current status of the measurements of the Higgs boson couplings to leptons, namely to muons and tau leptons, is summarized in the following sections.

2. Search for the Higgs boson decay into a pair of muons

Due to the small branching ratio, the search for the Higgs boson decay into a pair of muons is very challenging. However, the excellent di-muon mass resolutions achieved by the ATLAS and CMS experiments make this channel already accessible with an impressive sensitivity with the current amount of available data. In the described ATLAS search [13] data taken in the years 2015 and 2016 corresponding to an integrated luminosity of 36.1 fb^{-1} have been analyzed [1], while for the CMS analysis [15] only the data from the year 2016 corresponding to 35.9 fb^{-1} are taken into account.
The search strategy adopted by the two experiments is very similar. In both analyses two oppositely charged muon candidates produced in the central detector parts are selected. In the ATLAS analysis the invariant mass of the two muon candidates is studied in a window between 110 and 160 GeV, while in the CMS analysis the studied mass window is slightly smaller, from 110 to 150 GeV. In both cases the mass windows were chosen such that on one hand the Z boson peak is excluded from the analysis, but on the other hand enough data are selected to make a constrain of the normalization and shape of the SM background processes in this mass window feasible. In order to be able to not only probe Higgs boson production via gluon fusion (ggF) but also target Higgs boson production via vector boson fusion (VBF) an event category comprising events with at least two jets is introduced by both experiments. The main background processes of these searches are Drell-Yan production with the subsequent decay into a muon pair, while also top quark and di-boson productions contribute with significant portions.
In order to further enhance the search sensitivity, both experiments introduce several additional event categories. In the ATLAS analysis two categories enriched in VBF events are defined by imposing requirements on the output of a boosted decision tree (BDT). Additionally, six categories

[1] In the meantime, the ATLAS experiment has updated the results in this channel using data collected in the years 2015, 2016 and 2017 corresponding to an integrated luminosity of 79.8 fb^{-1} [14] .



(a) (b)

Figure 1: (a) Fit to the signal and background distributions for the ATLAS analysis in the VBF tight category. The figure is taken from [13]. (b) Signal plus background fit combined for all studied event categories weighted with the signal over background ratio in the CMS analysis. The figure is taken from [15].

enriched in the Higgs boson production mode via ggF are designed. These categories are defined by requirements on the transverse momentum spectrum of the system built from the two muon candidates and the pseudorapidity of the muon candidates. This way, the harder di-muon transverse momentum spectrum of events produced via ggF compared to SM background processes, and the excellent muon transverse momentum resolution in the central detector parts are made use of. These features of the signal events are also exploited by the CMS analysis by using these variables as input to a BDT. Other variables used in the BDTs of both experiments are variables describing the di-jet system of VBF events, like the di-jet mass and the pseudorapidity difference of the two jets. In the CMS analysis 15 event categories are defined by optimized cuts on the BDT output and on the pseudorapidity of the muon candidate with the largest pseudorapidity.

In all studied event categories analytic functions are used to describe the steeply falling di-muon mass spectrum of SM background processes in the studied mass window as well as the signal peaking around the Higgs boson mass. An example of these signal and background fits is shown for the ATLAS analysis in the VBF tight category in Fig. 1(a), while in Fig. 1(b) the signal plus background fit performed in the CMS analysis is shown for all studied event categories weighted with the signal over background ratio. In neither of the two analyses a significant excess is observed in any of the categories and upper limits are set on the production cross section times branching ratio with respect to the Standard Model expectation for the combined Run I and Run II data. In the ATLAS analysis an upper limit of 2.8 (2.9) is observed (expected) at 95% confidence level (C.L.), while the CMS experiment sets an upper limit of 2.92 (2.16) at 95% C.L. The best fit signal strength μ is $1.0 \pm 1.0(\text{stat}) \pm 0.1(\text{syst})$ in the CMS and -0.1 ± 1.4 in the ATLAS analysis. In all cases a Higgs boson mass of 125 GeV is assumed.

3. Observation of the Higgs boson decay into a pair of tau leptons

3.1 ATLAS analysis in the vector boson fusion and gluon fusion production modes

For the ATLAS search in the Higgs boson decay channel into a pair of tau leptons data collected in the years 2015 and 2016 corresponding to an integrated luminosity of 36.1 fb^{-1} have been analyzed [16]. The search targets the VBF and ggF production modes of the Higgs boson and is performed in the $e\mu$, ee, $\mu\mu$, $\mu\tau_h$, $e\tau_h$, and $\tau_h\tau_h$ decay channels of the tau lepton pairs, where τ_h denotes a hadronically decaying tau lepton candidate. Furthermore, only events that have at least one jet are considered for the analysis. The selected events are split into VBF categories and boosted categories. The VBF categories comprise events in which a second high-p_T jet is found in the detector hemisphere opposite to the one in which the p_T-leading jet has been found. Furthermore, a large invariant mass of the di-jet system is required. All VBF categories are dominated by events in which the Higgs boson has been produced via VBF processes. However, a contribution from Higgs bosons produced via ggF of up to 30% can be present.

The boosted categories are characterized by a high-p_T jet recoiling against the Higgs boson, such that the Higgs boson candidate built from the tau lepton candidates is expected to have a large transverse momentum. The boosted categories are dominated by events in which the Higgs boson has been produced via ggF. However, Higgs bosons produced via VBF and Higgs bosons produced in association with a vector boson can contribute between 10% and 20%. In all event categories the invariant mass of the Higgs boson candidate reconstructed from the visible tau lepton decay products and the measured missing transverse momentum using a likelihood approach [17] is used for the final statistical interpretation of the analysis.

In order to enhance the sensitivity of the search, both the boosted and the VBF categories are further split into different signal regions by imposing requirements on the transverse momentum of the system built from the tau lepton candidates, the angular distance between the tau lepton candidates, and the invariant mass of the di-jet system. Control regions are used to constrain the normalization of the top quark background processes and the Drell-Yan background processes with subsequent decay into a pair of electrons or muons in the signal region. Processes that classify as a background for this analysis because of a jet, an electron or a muon being mis-identified as a tau lepton candidate are estimated using data-driven techniques. The most dominant background process for this search is Drell-Yan production with tau leptons in the final state. This background is estimated using simulated events at next-to-leading order using the Sherpa event generator [18]. The normalization of this background is constrained in the signal regions during the final statistical interpretation of the search. Figure 2 shows a comparison of data to the SM background prediction in the distribution of the reconstructed Higgs boson candidate in one of the VBF signal regions in the $\tau_{\text{lep}}\tau_{\text{had}}$ channel.

With the presented search an observed (expected) significance of 4.4σ (4.1σ) is achieved assuming a Higgs boson mass of 125 GeV. The best-fit signal strength is found to be $\mu = 1.09^{+0.18}_{-0.17}(\text{stat})^{+0.27}_{-0.22}(\text{syst})^{+0.16}_{-0.11}(\text{theory syst})$. By performing a two-parameter scan the VBF and ggF production cross sections are determined. The cross sections are measured to be $\sigma^{\text{VBF}}_{H\to\tau\tau} = 0.28 \pm 0.09(\text{stat})^{+0.11}_{-0.09}(\text{syst})$ pb and $\sigma^{\text{ggF}}_{H\to\tau\tau} = 3.0 \pm 1.0(\text{stat})^{+1.6}_{-1.2}(\text{syst})$ pb. This is in agreement with the SM prediction. By combining the results with the data taken during Run I an observed (expected) significance of 6.4σ (5.4σ) is achieved. This confirms the observation of the Higgs boson

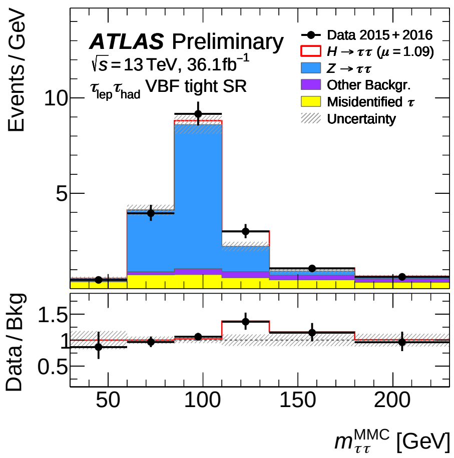
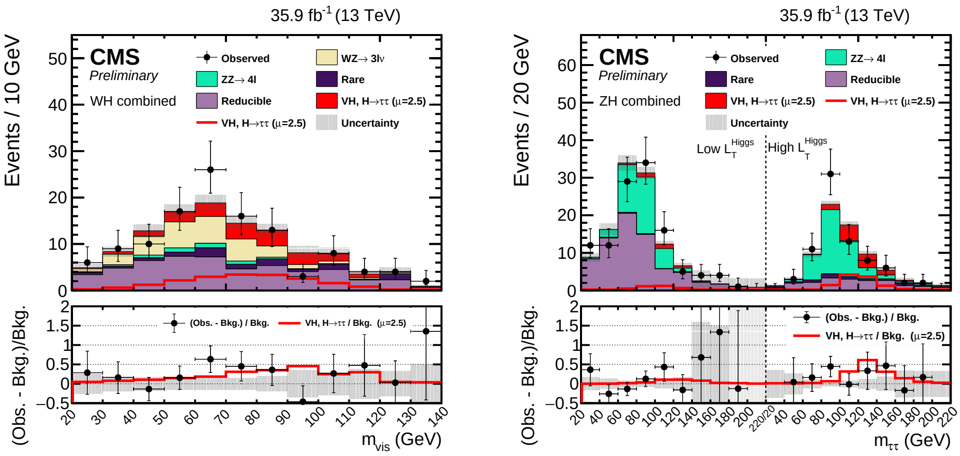


Figure 2: Comparison of data to the SM background prediction in the distribution of the reconstructed Higgs boson candidate in one of the VBF signal regions in the $\tau_{\text{lep}}\tau_{\text{had}}$ channel. The figure is taken from [16].

decay mode into a pair of tau leptons by the CMS experiment [19], where an observed (expected) significance of 5.9σ (5.9σ) and a best-fit signal strength of $\mu = 0.98 \pm 0.18$ at a Higgs boson mass of 125.09 GeV has been measured.

3.2 CMS analysis in the vector boson associated Higgs boson production

A search for the Higgs boson produced in association with a vector boson is performed in the Higgs boson decay channel into two tau leptons by the CMS experiment using data corresponding to an integrated luminosity of 35.9 fb^{-1} collected in the year 2016 [20]. The search for WH production is performed in the channels where the W boson decays into an electron or a muon and the corresponding neutrino, and the Higgs boson decays into a pair of tau leptons. The studied tau lepton decay modes are $\mu\tau_h$ and $\tau_h\tau_h$. The search for ZH production is performed in the channels where the Z boson decays into a pair of electrons or muons and the Higgs boson decays into a pair of tau leptons. The tau lepton final states covered in the ZH analysis are $e\mu$, $\mu\tau_h$, $e\tau_h$, and $\tau_h\tau_h$. In all ZH analysis channels the reconstructed Higgs boson mass is used for the extraction of the final results of the search. The Higgs boson candidate is reconstructed from the leptons not assigned to the Z boson decay using the likelihood-based reconstruction technique described in [21]. In the WH analysis channels the visible mass reconstructed either from the transverse momentum sub-leading light lepton candidate and the hadronically decaying tau lepton candidate, or from both hadronically decaying tau lepton candidates is used for the statistical interpretation of the search.
SM background processes arising from events where a jet is misidentified as a light lepton candidate or a hadronically decaying tau lepton candidate are estimated from data. Other background processes as di- and tri-boson production, top quark pair production in association with a vector boson or a Higgs boson, and processes with the Higgs boson decaying into a pair of vector bosons are estimated from simulation.
A comparison of data to simulation in the visible mass of all reconstructed decay products of the Higgs boson candidate combined for all WH categories is shown in Fig. 3(a). Figure 3(b) shows the comparison in the reconstructed mass of the Higgs boson candidate combined for all ZH chan-



(a) (b)

Figure 3: Comparison of data to simulation in (a) the visible mass of all reconstructed decay products of the Higgs boson candidate combined for all WH categories and (b) in the reconstructed mass of the Higgs boson candidate combined for all ZH channels, but divided into two different categories. The figures are taken from [20].

nels, but split into two different categories. The categories are thereby defined by requirements on the scalar sum of the transverse momenta of the particles produced in the decay of the Higgs boson candidate.

In the search a significance of 2.3σ (1.0σ) is observed (expected) for a Higgs boson produced in association with a vector boson in the decay channel to tau leptons. The best-fit signal strength μ is $2.54^{+1.35}_{-1.26}$.

The described VH analysis is combined with the analysis measuring the Higgs boson decay into a pair of tau leptons in the VBF and ggF production modes described in [19]. The combination with the VBF and ggF analysis follows what is presented in [19], except that a re-weighting of the transverse momentum spectrum of the Higgs boson in ggF events to the spectrum predicted by the NNLOPS generator [22] is performed, and that the uncertainties in the ggF production cross section have been updated according to [23]. In this combination the best-fit signal strength μ is $1.24^{+0.29}_{-0.27}$. The results correspond to an observed (expected) significance of 5.5σ (4.8σ). Thus, this combination marks the first analysis that reaches the observation level for Higgs boson decays into a pair of tau leptons with 2016 data alone.

4. Summary

In this review, the status of the analyses performed by the ATLAS and CMS collaborations that search for Higgs boson decays into pairs of charged leptons using LHC proton-proton collision data was presented. These measurements provide important tests of the Standard Model of particle physics as any deviation of the measurements with respect to the prediction could hint towards physics beyond the Standard Model. In the searches performed by the ATLAS and CMS collaborations for the Higgs boson decay into a pair of muons no significant excess has been observed by either of the experiments. Upper limits are set on the production cross section times branching ratio. However, a remarkable sensitivity has been achieved by both experiments already by analyzing the data taken during half of the LHC Run II run period. Moreover, a new result of the ATLAS collaboration in the Higgs boson decay channel into a pair of tau leptons has been presented. This analysis confirms the observation of the Higgs boson in this decay channel by the CMS collaboration. Additionally, a new CMS result looking for Higgs boson production in association with a vector boson in the Higgs boson decay channel into a pair of tau leptons was presented. By combining the search result with the CMS analysis performed in the VBF and ggF production modes the observation level is achieved in this decay channel with Run II data only.

References

[1] ATLAS Collaboration, Phys. Lett. B 716 (2012) 1, arXiv:1207.7214

[2] CMS Collaboration, Phys. Lett. B 716 (2012) 30, arXiv:1207.7235

[3] CMS Collaboration, JHEP 06 (2013) 081, arXiv:1303.4571

[4] ATLAS Collaboration, JINST 3 S08003 (2008)

[5] CMS Collaboration, JINST 3 S08004 (2008)

[6] ATLAS Collaboration, Phys. Lett. B 784 (2018) 345, arXiv:1806.00242

[7] CMS Collaboration, JHEP 11 (2017) 047, arXiv:1706.09936

[8] CMS Collaboration, submitted to JHEP, arXiv:1804.02716

[9] ATLAS Collaboration, Phys. Lett. B 784 (2018) 173, arXiv:1806.00425

[10] CMS Collaboration, Phys. Rev. Lett. 120 (2018) 231801, arXiv:1804.02610

[11] ATLAS Collaboration, submitted to Phys. Lett. B, arXiv:1808.08238

[12] CMS Collaboration, CMS-PAS-HIG-18-016, https://cds.cern.ch/record/2633415

[13] ATLAS Collaboration, Phys. Rev. Lett. 119 (2017) 051802, arXiv:1705.04582

[14] ATLAS Collaboration, ATLAS-CONF-2018-026, https://cds.cern.ch/record/2628763

[15] CMS Collaboration, submitted to Phys. Rev. Lett., arXiv:1807.06325

[16] ATLAS Collaboration, ATLAS-CONF-2018-021, http://cdsweb.cern.ch/record/2621794

[17] A. Elagin et al., Nucl. Instrum. Meth. A 654 (2011) 481

[18] T. Gleisberg et al., JHEP 02 (2009) 007, arXiv: 0811.4622

[19] CMS Collaboration, Phys. Lett. B 779 (2018) 283, arXiv:1708.00373

[20] CMS Collaboration, CMS-PAS-HIG-18-007, https://cds.cern.ch/record/2621550

[21] L. Bianchini, J. Conway, E. K. Friis, and C. Veelken, J. Phys. Conf. Ser. 513 (2014) 022035, doi:10.1088/1742-6596/513/2/022035

[22] K. Hamilton, P. Nason, E. Re, and G. Zanderighi, JHEP 10 (2013) 222, arXiv:1309.0017

[23] D. de Florian et al., CERN Report CERN-2017-002-M, arXiv:1610.07922