Evidence for Higgs Boson Decays to the $\tau^+\tau^-$ Final State with the ATLAS Detector

Nils Ruthmann on behalf of the ATLAS Collaboration.
Physikalisches Institut, Hermann-Herder-Str. 3
D-79104 Freiburg, Germany

After the discovery of a Higgs boson in the bosonic final states in 2012, the search for fermionic decay modes plays a crucial role in the identification of this particle as the Higgs boson of the Standard Model. Tau leptons, as the heaviest charged leptons, do contribute significantly to the decay width of the Higgs boson. Recent results on the search for Higgs boson decays to the $\tau^+\tau^-$ final state with the ATLAS detector are presented based on data corresponding to an integrated luminosity of 21 fb^{-1} collected at $\sqrt{s} = 8$ TeV. An excess of events with an observed (expected) significance corresponding to 4.1 (3.2) standard deviations (σ) is found. This provides evidence for $H \to \tau^+\tau^-$ decays consistent with the Standard Model expectation for a Higgs boson with $m_H = 125$ GeV.

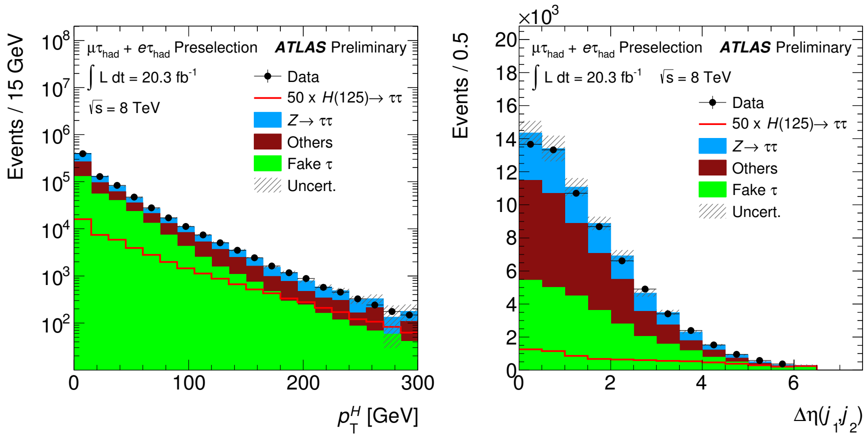
1 Introduction

The discovery of a Higgs boson by the ATLAS [1] and CMS [2] collaborations in 2012 in the bosonic final states $\gamma\gamma$, ZZ^* and WW^* opens up the possibility of detailed studies of the electroweak symmetry breaking sector of the Standard Model (SM). At the LHC, the Higgs boson is predominantly produced in the gluon fusion production mode (ggF) via a heavy quark loop, in the vector boson fusion mode (VBF) and in association with a vector boson (VH). Current analyses of coupling strengths [3], spin and CP quantum numbers [4] are all compatible with the SM predictions for a Higgs boson of mass $m_H = 125.5$ GeV, while a direct observation of Higgs boson decays into fermions was not made until recently [5]. The coupling strength of the Higgs boson to fermions could only be indirectly assessed in bosonic final states via the heavy quark loop contributions in the gluon fusion production and in $H \to \gamma\gamma$ decays. $H \to \tau^+\tau^-$ decays, with a branching ratio of 6.3%, can be used to directly measure the Higgs boson coupling strength to fermions. The tau leptons decay further into electrons, muons or hadrons. The ATLAS collaboration recently searched for a Higgs boson [6] in 20.3 fb^{-1} of proton proton collision data at $\sqrt{s} = 8$ TeV collected in the year 2012 in the fully leptonic $H \to \tau^+_{lep}\tau^-_{lep}$, the semi-leptonic $H \to \tau^+_{lep}\tau^-_{had}$ and fully hadronic final state $H \to \tau^+_{had}\tau^-_{had}$ [a]. The search is based on a boosted decision tree (BDT) classification to separate backgrounds from signal.

2 Event Selection and Categorization

Hadronic tau decays into one or three charged hadrons, a neutrino and additional neutral hadrons are reconstructed in ATLAS as narrow hadronic jets and are identified by a dedicated boosted decision tree algorithm exploiting various shower profile and isolation variables. For the $\tau^+_{lep}\tau^-_{lep}$ channel, events with exactly two isolated light leptons of opposite charge and no hadronic tau

[a] $\tau^{\pm}_{lep}$ denotes a leptonic tau decay $\tau^{\pm} \to \ell^{\pm}\nu_\tau\nu_\ell$ while $\tau^{\pm}_{had}$ denotes a hadronic tau decay $\tau^{\pm} \to$ had ν_τ



(a) (b)

Figure 1 – The p_T^H (a) and $\Delta\eta(j_1, j_2)$ (b) distributions in the $\tau_{lep}^{+}\tau_{had}^{-}$ channel used to define the analysis categories after preselection.

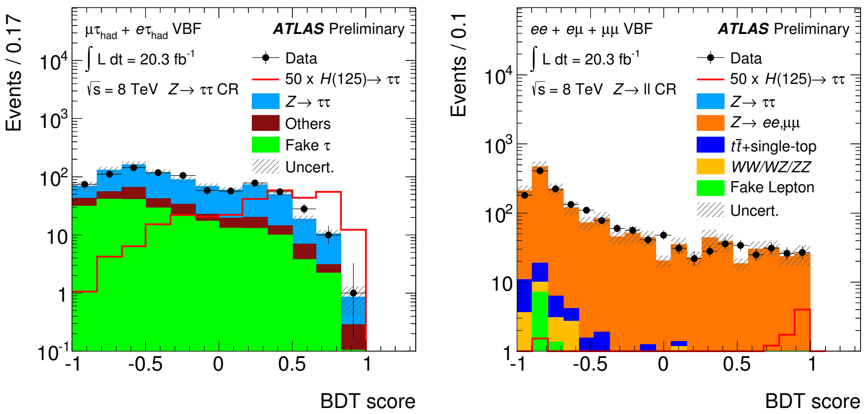
candidates are selected using single- and di-lepton triggers. Leptons triggering the event are required to fulfill offline transverse momentum thresholds adapted to the trigger threshold to ensure a high trigger efficiency. Additional electrons and muons are reconstructed above p_T thresholds of 15 and 10 GeV, respectively. The invariant mass of the two leptons is required to be 30 GeV $< m^{ll} <$ 100 GeV for the $e\mu$ final state, and $30 < m^{ll} < 75$ GeV for the same-flavor final state to suppress events with Z and other resonances decaying into leptons. In addition, events with $E_T^{\rm miss} <$ 40 GeV ($E_T^{\rm miss} <$ 20 GeV for the $e\mu$ final state) are rejected. Single lepton triggers are used to select events for the $\tau_{lep}^{+}\tau_{had}^{-}$ channel, requiring exactly one isolated light lepton and exactly one identified hadronic tau of opposite charge. To suppress events with a misidentified hadronic tau from $W+$jets events, the transverse mass[b] of the lepton and $E_T^{\rm miss}$ is required to be $m_T <$ 70 GeV. The lepton is selected above a p_T threshold of 26 GeV and the transverse momentum of the hadronic tau candidate is required to exceed 20 GeV. For the $\tau_{had}^{+}\tau_{had}^{-}$ channel, events with two hadronic tau candidates are selected using a ditau trigger and events with electron or muon candidates are rejected. The tau candidates are required to pass tight and medium identification criteria and the transverse momentum of the two taus have to exceed 35/25 GeV for the leading and subleading candidate, respectively. The opening angle between the two taus needs to satisfy $0.8 < \Delta R(\tau_{had}, \tau_{had}) < 2.8$ and $\Delta\eta(\tau_{had}, \tau_{had}) < 1.5$ to suppress the large multijet background. In all three channels, additional jets with $p_T >$ 30 GeV ($p_T >$ 35 GeV in the hadronic channel) clustered by the anti-k_T algorithm with a distance parameter of $R = 0.4$ are selected. Jets within the tracker acceptance are required to be matched to the primary vertex of the event. Within pseudorapidities of $|\eta| < 2.5$, b-jets are identified using a tagging algorithm with a selection efficiency of about 60% and a light quark jet misidentification rate of $0.1 - 0.5\%$.

Given that the analysis makes use of BDTs to isolate phase space regions of high signal purity, only a loose preselection and categorization is applied to the initial event sample. Two categories are built, targeting the topology of the two main Higgs boson production modes. The VBF category is defined by the presence of two jets with a large separation in pseudorapidity and is enriched in VBF events, with fractional contributions ranging from 55% to 75% depending on the final state. The boosted category contains events with a large transverse momentum of the reconstructed Higgs boson candidate leading to a better ditau mass resolution. The signal contribution is dominated by ggF events (70%-75%) with one or two additional hard jets while only a small VBF contribution is present. Figure 1 shows the p_T^H and $\Delta\eta(j_1, j_2)$ distributions

[b] $m_T = \sqrt{2 p_T^{\ell} E_T^{\rm miss}(1 - \cos\Delta\phi(\ell, E_T^{\rm miss}))}$

in the $\tau_{lep}^{+}\tau_{had}^{-}$ channel, used to define the categories. In the fully leptonic and semi-leptonic channels, both categories exclude events with an identified b-jet to reduce the contamination from top pair production.

3 Background Estimation and Discrimination



(a) (b)

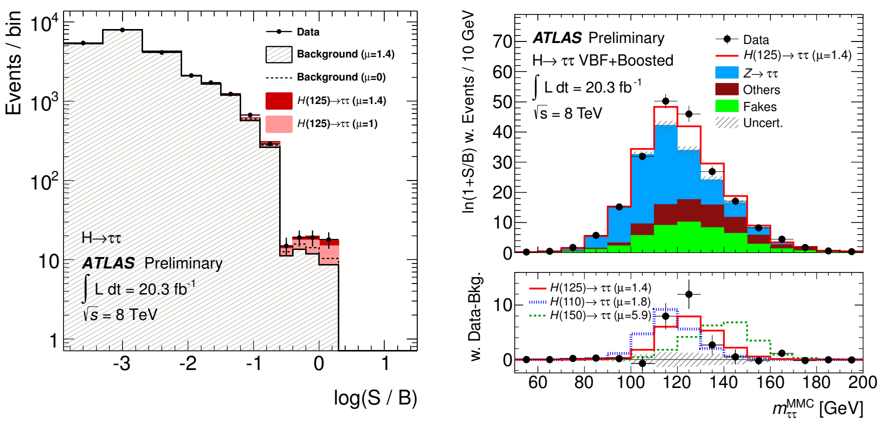
Figure 2 – Validation regions enriched in $Z \to \tau^{+}\tau^{-}$ (a) and $Z \to \ell\ell$ (b) events in the VBF category of the $\tau_{lep}^{+}\tau_{had}^{-}$ and $\tau_{lep}^{+}\tau_{lep}^{-}$ channels, respectively.

In all channels and categories, BDTs are used to separate signal from background processes. The main background in all channels stems from $Z \to \tau^{+}\tau^{-}$ decays. In the $\tau_{lep}^{+}\tau_{lep}^{-}$ channel $Z \to \ell\ell$ and $t\bar{t}$ events as well as events with a misidentified lepton represent additional backgrounds. Events with misidentified taus are an important background source for the $\tau_{lep}^{+}\tau_{had}^{-}$ and $\tau_{had}^{+}\tau_{had}^{-}$ channels, stemming from $W +$ jets, $Z +$ jets, $t\bar{t}$ and multijet events. In order for suppression of these backgrounds, a variety of discriminating variables is used. The topology of the two leading jets in the VBF category plays a crucial role to suppress $Z \to \tau^{+}\tau^{-}$ events. Angular variables describing the topology of the reconstructed ditau system are used to suppress non-resonant backgrounds with misidentified taus, and variables describing the overall event topology allow suppressing backgrounds with jet activity different from that present in signal events. Between five and nine variables are used as input to the BDT, depending on category and channel. The BDTs in the VBF category are trained solely targeting the isolation of VBF events, while the BDTs in the boosted category target all signal processes. A signal mass hypothesis of $m_H = 125$ GeV is used in the training procedure.

The backgrounds are mostly modelled in a data driven way to minimize systematic uncertainties. The main $Z \to \tau^{+}\tau^{-}$ background is modelled by $Z \to \mu\mu$ data in which the muons are replaced by simulated tau leptons. This allows building a fully data driven model of the jet topology and the kinematic properties of the Z boson. A non-isolated lepton control region is used to model $W +$ jets, multijet and semi-leptonic $t\bar{t}$ events in $\tau_{lep}^{+}\tau_{lep}^{-}$ channel. The tau misidentification rate is measured in regions enriched in $W +$ jets and multijet events for the $\tau_{lep}^{+}\tau_{had}^{-}$ channel. These rates are applied as extrapolation factor to events in a control region with inverted tau identification criteria to model events with misidentified taus in the signal region. In the $\tau_{had}^{+}\tau_{had}^{-}$ channel, events failing the charge correlation criteria are used to model the shape of the multijet background, while its normalization is determined in the combined likelihood fit. Various validation regions are used to validate the background model. A good modelling is observed for all input variables, all linear correlations between the input variables, and for the BDT score distributions in the validation regions. Figure 2 shows the BDT score distribution in validation regions enriched in $Z \to \tau^+\tau^-$ and $Z \to \ell\ell$ events in the $\tau_{lep}^+\tau_{had}^-$ and $\tau_{lep}^+\tau_{lep}^-$ channels, respectively, in the VBF category.

4 Results

A combined maximum likelihood fit is performed on the BDT distributions in all categories and channels and some control regions constraining certain background components. Besides the signal strength modifier ($\mu = \sigma^{\text{meas.}}/\sigma^{\text{SM}}$), various background normalizations are determined in parallel. The effect of systematic uncertainties are parametrized and reflected as nuisance parameters in the fit. The major systematic uncertainties originate from theoretical uncertainties on the p_T^H spectrum of ggF events, jet energy scale uncertainties and $Z \to \ell\ell$ and $t\bar{t}$ background normalizations in the $\tau_{lep}^+\tau_{had}^-$ channel. The signal strength modifier is measured to be $\mu = 1.43^{+0.31}_{-0.29}(\text{stat.})^{+0.41}_{-0.30}(\text{syst.})$ for a signal mass hypothesis of $m_H = 125$ GeV. To quantify the agreement of the observed data with the background only hypothesis, a test statistic $q_{\mu=0} = -2\ln(\mathcal{L}(\mu=0,\hat{\hat{\vec{\theta}}})/\mathcal{L}(\hat{\mu},\hat{\vec{\theta}}))$ is constructed and the asymptotic approximation [7] is used to determine its probability density function. The probability to observe a background fluctuation in data at least as signal-like as obtained is 2×10^{-5} corresponding to an observed significance of 4.1 σ while a significance of 3.2σ is expected. This result therefore yields evidence for $H \to \tau^+\tau^-$ decays and is in good agreement with the SM expectation. Figure 3 (a) shows the event yields in all categories and channels as a function of their expected sensitivity, clearly demonstrating the observed excess in the signal sensitive bins. Figure 3 (b) shows the ditau mass distribution, where each event is weighted by its expected significance based on the BDT output. The observed excess is compatible with the expectation of a Higgs boson of mass $m_H = 125$ GeV.



(a) (b)

Figure 3 – Event yields as a function of $\log(S/B)$ compared to the background only and the signal + background hypothesis with SM signal strength ($\mu = 1$) and the result of the combined fit (a). Figure (b) shows the mass distribution after weighting events based on the expected signal purity in each BDT bin.

References

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