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Evidence for the 125 GeV Higgs Boson Decaying into Taus at the CMS Experiment

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Abstract

A search for a standard model (SM) Higgs boson decaying into a pair of τ leptons is performed using events recorded by the CMS experiment at the LHC in 2011 and 2012. The dataset corresponds to an integrated luminosity of 4.9 fb^{-1} at a centre-of-mass energy of 7 TeV and 19.7 fb^{-1} at 8 TeV. Each τ lepton decays hadronically or leptonically to an electron or a muon, leading to six different final states for the τ -lepton pair, all considered in this analysis. An excess of events is observed over the expected background contributions, with a local significance larger than 3 standard deviations for m_H values between 115 and 130 TeV. The best fit of the observed $H \rightarrow \tau\tau$ signal cross section times branching fraction for $m_H = 125 \text{ GeV}$ is 0.78 ± 0.27 times the standard model expectation. These observations constitute evidence for the 125 GeV Higgs boson decaying into a pair of τ leptons.

Keywords: LHC, CMS, Higgs, Tau

1. Introduction

The study of Higgs bosons is one of the major goals at the LHC. Both the ATLAS and the CMS experiment have observed the Higgs boson in a combined search in the five dominant decay channels ($ZZ \rightarrow 4l$, $\gamma\gamma$, $WW \rightarrow 2l2\nu$, $\tau\tau$ and $b\bar{b}$) [1, 2]. The observation was driven by the high resolution channels, namely the decays into two Z boson and two photons. The aim of both group was to also establish the fermionic decay modes of the Higgs boson. Here, the search for the Higgs boson decaying into τ leptons at the CMS experiment is presented. The entire run I dataset collected with the CMS detector at the LHC in the years 2011 and 2012 with an integrated luminosity of 4.9 fb^{-1} at $\sqrt{s} = 7 \text{ TeV}$ and 19.7 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$ has been analysed. The focus here is on analysis methods that are unique in final states containing τ leptons. A complete documentation of this analysis has been published in [3].

2. The search for the Higgs boson decaying into a pairs of taus

The $H \rightarrow \tau\tau$ channel is characterised by a relatively large branching ratio of about 6.3% at $m_H = 125 \text{ GeV}$ [4] accompanied by manageable background contaminations. Main backgrounds are Z boson decays as well as $t\bar{t}$, W +jets, di-boson production and QCD events. Their relative contributions depend on the $\tau\tau$ decay mode.

All six possible $\tau\tau$ decay modes, namely fully hadronic ($\tau_h\tau_h$), semi-leptonic ($\mu\tau_h$ and $e\tau_h$) and fully leptonic ($e\mu$, $\mu\mu$ and ee), are analysed for the gluon fusion (GF) and vector boson fusion (VBF) Higgs boson production modes. A dedicated analysis for the production in association with vector bosons (VH) completes the analysis. The categorisation employing the various production and decay modes is described in section 2.1.

Up to four neutrinos in the final state complicate the measurement of the invariant di- τ mass and with it the

separation of H and Z events. This makes a sophisticated mass reconstruction method necessary as described in section 2.2.

Based on the reconstructed mass as a central observable, the estimation of the dominant $Z \rightarrow \tau\tau$ background is explained in section 2.3. The estimation of τ -related uncertainties is discussed in section 2.4 before the results are presented in section 2.5.

2.1. Event categories

Events are classified into categories in order to exploit the differences in Higgs production and decay mode and to isolate regions with enhanced signal to background ratios. For each decay mode a separate sub-analysis exists.

Furthermore, events are categorised by the jet multiplicity. Events with two forward jets, a large gap in the pseudorapidity in between and a large di-jet mass are tagged as VBF events. The VBF production is crucial for the Higgs search because it is characterised by a small background contamination. Events with one jet mainly result from GF events where one of the initial partons radiates gluon forming a jet. The GF production is the dominant Higgs boson production mode at the LHC with a cross section about ten times larger than the one of VBF. Zero jet events suffer from large background contaminations and are therefore mainly used to constrain the background related systematic uncertainties. The VH analysis exploits events with higher lepton multiplicities in the final state.

Finally, events are partitioned into categories according to the lepton p_T and di-jet quantities in the VBF category in order to increase the sensitivity. Because of its higher mass the spectra of the lepton p_T are harder for Higgs boson decays than for Z decays.

2.2. Mass reconstruction

The reconstruction of the invariant di- τ mass is crucial for the separation of signal- and background-like events. One can measure the four-momenta of the visible τ decay products (electrons, muons or so-called τ jets) as well as the two components of the missing transverse energy (MET). The components of the individual neutrino momenta can be parametrised as functions of the measured quantities. However, this gives an under-determined system of equations. Therefore the most probable configuration is estimated based on a likelihood function evaluating the compatibility of the measured momenta with phase space information from matrix element calculations. This gives then the most probable di- τ mass.

Figure 1 shows the mass of the visible decay products (left) and the reconstructed di- τ mass (centre). It is clearly visible, that the resolution and therefore also the separation power is significantly improved. Another advantage is, that the mean gets shifted towards the true mass for signal events and the most dominant $Z \rightarrow \tau\tau$ background. Other backgrounds like $t\bar{t}$ and QCD events show a more flat distribution in the mass.

In most of the event categories the reconstructed di- τ mass is taken as the final observable. Exceptions are the $\mu\mu$ and ee categories, where a multivariate discriminator suitable for the suppression of the overwhelming $Z \rightarrow \mu\mu$ and $Z \rightarrow ee$ backgrounds is used, and the WH categories, where the mass of the visible decay products is used. Based on the final observable statistical results are obtained.

Figure 1: The reconstructed di- τ mass (centre) provides a better resolution compare to the mass of the visible decay products (left). The τ energy scale and its uncertainty are derived from a template fit of the visible mass of the hadronically decaying τ to data (right). [3]

2.3. Background estimation

The precise knowledge of the background contributions is crucial for the search for the small Higgs boson signal. Data-driven methods are exploited as much as possible in order to reduce the systematic uncertainties from theoretical predictions. This is especially needed and true for the most dominant irreducible background from $Z \rightarrow \tau\tau$ events.

The $Z \rightarrow \tau\tau$ background is estimated from data using the embedding technique. A clean $Z \rightarrow \mu\mu$ sample is selected around the Z peak. In CMS muons can be identified very efficiently and their momenta measured with a high accuracy. In each event, the measured muons are then replaced by simulated τ leptons with the same momenta as the original muons. In this hybrid event contributions from the underlying event and pile-up jets as well as the experimental part of the MET are preserved from data and only the τ decay products result from simulation.

For many of the other backgrounds, the mass shapes from MC simulation are taken and are normalised to data in sideband control regions. The QCD contribution is taken from data where same-sign charged leptons are selected.

2.4. Systematic uncertainties

Systematic uncertainties are estimated for the identification and reconstruction of the measured objects, the different background estimation methods and theory predictions as well as for limitations resulting from the size of the simulated samples. This section focusses on the τ energy scale and its uncertainty as the main source of systematic uncertainty for channels including hadronically decaying τ leptons.

Hadronically decaying τ leptons are reconstructed by the HPS algorithm [5]. The four dominant decay modes are handled individually, namely one prong decays (one charged pion together with zero, one or two neutral pions) and three prong decays (three charged pions). The energy scale is measured using a template fit which compares the simulated distribution of the τ jet mass with the measured one from data (see figure 1, right). The fit also estimates the uncertainty on the τ energy scale parameter to 3% per τ .

Additionally, normalisation uncertainties of 6-10% for the identification of τ leptons are taken into account. For background contributions, where a τ has been misidentified, the uncertainty is 20-80%. In the view of τ identification fake rates smaller than 1%, the overall impact of this uncertainty is small and dominated by statistical errors.

Figure 2: Example of the final di- τ mass distribution, here shown for the $\mu\tau_h$ channel and the VBF category [3].

2.5. Statistical inference and results

The final mass plots already reveal an excess of the data above the background only hypothesis in the most sensitive categories which is, however, still compatible with the background only hypothesis. See figure 2 as an example. The combined sensitivity of this excess in all event categories is determined to be 3.2σ (observed) and 3.7σ (expected) at the Higgs mass hypothesis of $m_H = 125$ GeV, the mass measured in the high-precision channels $H \rightarrow ZZ$ and $H \rightarrow \gamma\gamma$. This is the direct evidence for Higgs boson decays into pairs of τ leptons at the CMS experiment. The di- τ final state is also sensitive to $H \rightarrow WW$ events, especially in the $e\mu$ channel. In order to study the properties of the $H \rightarrow \tau\tau$ signal, contributions from $H \rightarrow WW$ have been treated as a background process according to the predictions from the standard model.

A likelihood scan is provided to determine the mass of the resonance leading to the seen excess. It is shown in figure 3 (left). The mass in the $\tau\tau$ channel is measured to $m_H = 122 \pm 7$ GeV. Within its uncertainties this result is compatible with the result obtained in the high-resolution channels and shows that there is an excess in form of a resonance.

All properties of the standard model Higgs boson can be predicted as a function of one single parameter, which is normally chosen as the mass of the Higgs boson. The measurement of Higgs boson properties is therefore an important consistency check for the standard model and possible new physics beyond the SM could become manifest in deviations of these measurements from SM predictions.

Figure 3: The mass scan (left) yields $m_H = 122 \pm 7$ GeV. The signal strengths of the five dominant Higgs decay modes displayed as coupling modifiers κ_i is in good agreement with SM expectation (centre) and is consistent with the Higgs mechanism predicting mass dependent couplings. The most stringent bounds on the couplings of the Higgs boson to fermions, denoted by κ_f , are given by the $H \rightarrow \tau\tau$ channel (right). [3, 6].

The signal strength modifier $\mu = \sigma/\sigma_{\text{SM}}$ is measured to be $\mu = 0.78 \pm 0.27$ in the $\tau\tau$ channel. This result is in good agreement with the standard model. Coupling modifiers κ_i are defined for the couplings of the Higgs boson to particles of class i as the deviations from the SM expectations. In figure 3 (centre) the coupling modifiers κ_i for the five most important Higgs boson decay modes are shown. The good agreement with the expectation of one in all channels indicates that the mass dependent Higgs boson couplings are as predicted by the Higgs mechanism. This is consistent with the hypothesis that the Higgs mechanism is responsible for the generation of the mass of elementary particles.

The couplings of the Higgs boson to vector bosons are fundamentally different from the Yukawa-type couplings to fermions. One of the main goals of the $H \rightarrow \tau\tau$ analysis is the study of these fermionic Higgs boson couplings. Figure 3 (right) shows the coupling modifiers κ_f for fermions versus to the coupling modifiers κ_v for vector bosons. The results emphasise the importance of the $\tau\tau$ channel showing that the bounds on the fermionic coupling are most stringent in this channel. In the analysis of the LHC run I data a precision of 30% on this coupling is reached by the $H \rightarrow \tau\tau$ analysis.

The results of this channel have been combined with the search for Higgs bosons decaying into pairs of b quarks resulting in an observed (expected) significance of 3.8σ (4.4σ) [7]. This shows the clear evidence for couplings of the Higgs boson to (down-type) fermions.

3. Conclusion

The search for the Higgs boson in the di- τ final state as published in [3] has been presented. An excess with the evidence of 3.2σ has been found. All measurements of the excess are in good agreement with the Standard Model prediction within their uncertainties. Based on this result, also the evidence for couplings of the Higgs boson to fermions can be claimed.

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