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Search for the standard model Higgs boson in the $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \tau^+ \tau^-$ decay channel in pp collisions at $\sqrt{s} = 7 \text{ TeV}$

The CMS Collaboration*

Abstract

A search is reported for the standard model Higgs boson in the $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \tau^+ \tau^-$ decay mode, where $\ell = \mu$ or e , in proton-proton collisions at $\sqrt{s} = 7 \text{ TeV}$, corresponding to an integrated luminosity of 4.7 fb^{-1} collected with the CMS detector at the LHC. No evidence is found for a significant deviation from the background expectation. An upper limit four to twelve times larger than the predicted value is set at 95% confidence level for the product of the standard model Higgs boson production cross section and decay branching fraction in the mass range $190 < m_H < 600 \text{ GeV}$.

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*See Appendix A for the list of collaboration members

1 Introduction

The search for the standard model (SM) [1–3] Higgs boson is one of the main goals of the Large Hadron Collider (LHC) physics programme. The discovery of the SM Higgs boson would shed light on the spontaneous electroweak symmetry breaking mechanism [4–9]. To date, experimental searches for this particle have yielded null results. Limits at 95% confidence level (CL) on its mass have been placed by experiments at LEP, $m_H > 114.4 \text{ GeV}$ [10], the Tevatron, $m_H \notin (162\text{--}166) \text{ GeV}$ [11], and ATLAS, $m_H \notin (145\text{--}206), (214\text{--}224), (340\text{--}450) \text{ GeV}$ [12–14]. Precision electroweak measurements, not taking into account the results from direct searches, indirectly constrain the SM Higgs boson mass to be less than 158 GeV [15].

This letter presents a search for the SM Higgs boson in the decay mode $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \tau^+ \tau^-$, where ℓ is either μ or e . One Z is required to decay either into $\mu^+ \mu^-$ or $e^+ e^-$, and the second Z into $\tau^+ \tau^-$ in four possible final states: $\tau_h \tau_h$, $\tau_\mu \tau_h$, $\tau_e \tau_h$, and $\tau_e \tau_\mu$, where τ_h represents a τ decaying hadronically, and τ_μ , and τ_e indicate taus decaying into muons and electrons respectively. The present measurement complements the search in the $H \rightarrow ZZ \rightarrow 4\ell$ channel [16]. The presence of four leptons in the final state provides a clean signature with only a small contribution from background processes. The major irreducible background contribution is non-resonant ZZ production. The most important reducible background contributions are Z and WZ production in association with jets, and $t\bar{t}$ production. The final states $\tau\tau \rightarrow \tau_\mu \tau_\mu, \tau_e \tau_e$ are not considered, as they are accounted for in the $H \rightarrow ZZ \rightarrow 4\ell$ Higgs search [16]. The cross sections for the Higgs boson production mechanisms and decay branching fractions, together with their uncertainties, are taken from Ref. [17] and are derived from Refs. [18–37].

The analysis is based on data from proton-proton collisions at $\sqrt{s} = 7 \text{ TeV}$, corresponding to an integrated luminosity of 4.7 fb^{-1} collected with the Compact Muon Solenoid (CMS) detector at the LHC in 2011. This is the first Higgs boson search performed in the $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \tau^+ \tau^-$ channel.

2 CMS Detector

A detailed description of the CMS detector can be found elsewhere [38]. The central feature of the CMS apparatus is a superconducting solenoid, of 6 m internal diameter, providing a magnetic field of 3.8 T . Within the field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter (ECAL), and the brass/scintillator hadron calorimeter. Muons are measured in gas-ionization detectors embedded in the steel return yoke.

CMS uses a right-handed coordinate system, with the origin at the nominal interaction point, the x -axis pointing to the centre of the LHC ring, the y -axis pointing up (perpendicular to the LHC plane), and the z -axis along the counterclockwise-beam direction. The polar angle, θ , is measured from the positive z -axis and the azimuthal angle, ϕ , is measured in the x - y plane. Variables used in this analysis are the pseudorapidity, $\eta = -\ln[\tan(\theta/2)]$, and the transverse momentum, $p_T = \sqrt{p_x^2 + p_y^2}$.

The ECAL is designed to have both excellent energy resolution and high granularity, properties that are crucial for reconstructing electrons and photons produced in τ -lepton decays. The ECAL is constructed with projective lead tungstate crystals that provide coverage in pseudorapidity $|\eta| < 1.479$ in a barrel region and $1.479 < |\eta| < 3.0$ in two endcap regions (EE). A preshower detector consisting of two planes of silicon sensors interleaved with a total of $3 X_0$ of lead is located in front of the EE. The energy resolution is 3% or better for the range of electron energies relevant for this analysis.

The inner tracker measures charged particle tracks within the range $|\eta| < 2.5$. It consists of 1 440 silicon pixel and 15 148 silicon strip detector modules, and provides an impact parameter resolution of $\sim 15 \mu\text{m}$ and a transverse momentum resolution of about 1.5% for 100 GeV particles. The reconstructed tracks are used to measure the location of interaction vertices. The spatial resolution of the reconstruction is $\approx 25 \mu\text{m}$ for vertices with more than 30 associated tracks [39].

The muon barrel region is covered by drift tubes, and the endcap regions by cathode strip chambers. In both regions, resistive plate chambers provide additional coordinate and timing information. Muons are reconstructed in the range $|\eta| < 2.4$, with a typical p_T resolution of $\approx 1\%$ for $p_T \approx 40 \text{ GeV}$.

3 Event Selection and Monte Carlo Samples

At the trigger level, the selected events are required to have at least two muons, one with $p_T > 13 \text{ GeV}$ ($p_T > 17 \text{ GeV}$ for the end of the data-taking period when the instantaneous luminosity was highest) and the other with $p_T > 8 \text{ GeV}$, or at least two electrons, one with $p_T > 17 \text{ GeV}$ and the other with $p_T > 8 \text{ GeV}$.

Algorithms for identifying muons and electrons, collectively referred to as leptons, are based on the tracker, the muon systems and the calorimeters [40, 41]. Since the ZZ final state is expected to have only a small contribution from background processes, the algorithms are tuned to maximize the lepton-reconstruction efficiency, resulting in an increased lepton-misidentification rate. A particle flow (PF) technique [42] is used to form lepton-isolation quantities and is also used for τ_h reconstruction. In the PF approach, information from all subdetectors is combined to reconstruct and identify particles produced in the collision. The particles are classified into mutually exclusive categories: charged hadrons, photons, neutral hadrons, muons, and electrons. These particles are used to reconstruct τ_h with the “hadron plus strip” (HPS) algorithm [43] that is designed to optimize the performance of τ_h identification and reconstruction by considering specific τ_h decay modes. The neutrinos produced in all τ decays escape detection and are ignored in the τ_h reconstruction. The algorithm provides high τ_h identification efficiency, approximately 50% for the range of τ_h energies relevant for this analysis, while keeping the misidentification rate for jets at the level of $\approx 1\%$, that is factor of three to four times lower with respect to other available algorithms [44].

Events are required to have at least one $Z \rightarrow \ell^+ \ell^-$ candidate, denoted by Z_1 , with the leptons of opposite charge, one with $p_T > 20 \text{ GeV}$ and another with $p_T > 10 \text{ GeV}$, and with $|\eta| < 2.4$ for the muons and $|\eta| < 2.5$ for the electrons. Both leptons are required to have a combined PF relative isolation $I_{\text{rel}}^{\text{PF}} < 0.25$, which is defined as:

$$I_{\text{rel}}^{\text{PF}} = \left(p_T^{\text{charged}} + \max(E_T^\gamma + E_T^{\text{neutral}} - 0.5 \times p_T^{\text{PU}}, 0) \right) / p_T^\ell, \quad (1)$$

where p_T^{charged} is the scalar sum of the charged hadrons p_T , and E_T^γ and E_T^{neutral} correspond, respectively, to the sum of the transverse energies of the photons and neutral hadrons, all measured in the isolation cone of $\Delta R < 0.4$ around the lepton direction, where $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$. The contribution from neutrals is corrected for the effect of overlapping pp interactions. The value of the correction is estimated by scaling the sum of the p_T of all charged particles not associated with the vertex in the isolation cone (p_T^{PU}) by a factor 0.5, which is approximately the ratio of neutral to charged hadron yields in hadronization processes.

For the second Z, denoted by Z_2 , the selection requirements depend on the final state. If the

final state is $\tau_\mu\tau_e$, the lepton p_T values are required to exceed 10 GeV. The remaining criteria are identical to those for Z_1 . Since τ_h s have much larger misidentification rates than the other leptons, the isolation requirement based on $I_{\text{rel}}^{\text{PF}}$ for the muons and electrons in the final states $\tau_\mu\tau_h$ and $\tau_e\tau_h$ is changed to 0.15 and 0.1, respectively. In a study of inclusive $Z \rightarrow \tau\tau$ production [45], it was demonstrated that modifying the muon and electron isolation requirements is a more effective way to reduce background in such final states than requiring tighter isolation on τ_h . The τ_h are required to have $p_T > 20$ GeV and $|\eta| < 2.3$, and to pass a loose HPS working-point requirement. If the Z_2 decays to $\tau_h^+\tau_h^-$, both τ_h are required to pass a medium working point of the HPS algorithm. The loose (medium) working point requires the scalar sum over the charged hadrons p_T and the neutral hadrons E_T in the isolation cone, to be less than 2 GeV (1 GeV). The loose (medium) working point corresponds to a probability of approximately 1% (0.5%) for jets to be misidentified as τ_h . Using the medium instead of loose working point leads to a decrease in the τ_h reconstruction efficiency from $\approx 50\%$ to $\approx 40\%$.

The visible invariant mass of the reconstructed $Z_2 \rightarrow \tau^+\tau^-$ is required to be $30 < m_{\tau\tau} < 80$ GeV, and this criterion is used for most of the final states. The upper bound reduces contributions from $Z_2 \rightarrow \ell\ell$, where a muon or an electron is not well reconstructed, and misidentified as a τ_h . For the $Z_2 \rightarrow \tau_e\tau_\mu$ final state, the upper bound is increased to 90 GeV, as this state is not produced in $Z_2 \rightarrow \ell\ell$ decays. Leptons from the same Z are required to be separated by $\Delta R > 0.4$ for Z_1 , and by $\Delta R > 0.5$ for Z_2 . The two reconstructed Z_1 and Z_2 are required to be separated by $\Delta R > 0.5$.

A set of Monte Carlo (MC) event samples is used to simulate signal and background events. The Drell–Yan background, $\ell^+\ell^-$ in association with jets, is simulated with the next-to-leading order (NLO) MC generator POWHEG 2.0 [46–48]. The QCD multijet, W and diboson WZ backgrounds are simulated with PYTHIA 6.424 [49]. The ZZ background is simulated with PYTHIA 6.424 and MADGRAPH [50]. The $t\bar{t}$ samples are simulated with MADGRAPH. The τ -lepton decays are generated with TAUOLA [51]. The Higgs boson samples are generated using POWHEG 2.0, which incorporates NLO gluon fusion ($gg \rightarrow H$) and vector-boson fusion ($qq \rightarrow qqH$). All events are processed through a detailed simulation of the CMS detector based on GEANT4 [52] and reconstructed with the same algorithms that are used for data.

4 Background Estimates and Systematic Uncertainties

The major irreducible source of background to the $H \rightarrow ZZ \rightarrow \ell^+\ell^-\tau^+\tau^-$ process is from SM $ZZ \rightarrow \ell^+\ell^-\tau^+\tau^-$ production. The ZZ contribution is estimated from data by scaling the prediction from simulation to the well measured inclusive Z production cross section. The number of estimated ZZ events, N_{ZZ}^{est} , can be written as:

$$N_{ZZ}^{\text{est}} = N_Z^{\text{obs}} \cdot \frac{\sigma_{ZZ}^{\text{SM}}}{\sigma_Z^{\text{SM}}} \cdot \frac{A_{ZZ}}{A_Z}, \quad (2)$$

where N_Z^{obs} is the number of observed events from inclusive Z production, A_Z is their estimated acceptance from a MC simulation, including all selection requirements, and rescaled by measured data/MC correction factors, A_{ZZ} is the acceptance for ZZ events, σ_Z^{SM} is the SM cross section for inclusive Z production, and σ_{ZZ}^{SM} is the SM cross section for ZZ production calculated with MCFM [53].

The other major background contributions arise from the production of Z and WZ in association with jets, as well as $t\bar{t}$ and QCD multijet production. The latter two backgrounds are small. In all these cases, a jet or non-isolated lepton is misidentified as a τ_h , τ_e or τ_μ . The probability

for jets to be misidentified as τ_h is measured using $\ell^+\ell^-\tau_h\tau_h$ events in data in which the Z_1 passes all selection requirements, but no requirement is applied on τ_h isolation, and the two τ_h candidates are required to have the same charge. This region is dominated by Z +jets events. The τ_h misidentification rate is defined as the ratio of the number of τ_h candidates that pass the HPS loose or medium working-point requirements, to the initial number of τ_h candidates, and is measured as a function of the p_T for each τ_h . To estimate the number of background events in the signal region, the measured misidentification rate is applied to events that pass all selection requirements, including the opposite-charge requirement for the Z_2 , but requiring the τ_h candidates to not be isolated.

The misidentification rate for τ_e and τ_μ in the $\mu\mu\tau_\mu\tau_e$ and $ee\tau_\mu\tau_e$ final states is estimated using events in which the Z_1 passes all selection requirements, and the event contains an additional muon or electron. No isolation requirements are applied to it. The misidentification rate is defined for τ_e and τ_μ in the same way as described above for τ_h and applied to $\mu\mu\tau_\mu\tau_e$ and $ee\tau_\mu\tau_e$ events that pass all the selection requirements, but requiring τ_e or τ_μ to not be isolated. Isolated muons and electrons from $H \rightarrow ZZ \rightarrow 4\ell$ and $ZZ \rightarrow 4\ell$ production can also be misidentified as τ_h . Events are rejected if they are also identified as $ZZ \rightarrow 4\ell$ events with criteria described in Ref. [16].

Theoretical uncertainties on the Higgs boson cross section (17–20%) and branching ratio (2%) are taken from Ref. [17]. Recent studies [17, 54, 55] show that current MC simulations do not describe the correct Higgs boson mass line shape above ≈ 300 GeV. This effect amounts to an additional uncertainty on the theoretical cross section, and hence on the limits, of about 4% at $m_H = 300$ GeV and 10–30% for m_H of 400–600 GeV. The main uncertainty on the estimate of the ZZ background arises from the theoretical uncertainty on the ZZ production cross section and is taken from Ref. [56]. The uncertainties on the other backgrounds, Z +jets, WZ +jets, and $t\bar{t}$ reflect the uncertainties on the measured values of the misidentification rates and the limited statistics of the control regions in the data. The uncertainty on integrated luminosity of the data sample is 4.5% [57]. Systematic uncertainties on trigger efficiency (1%) and on lepton identification efficiency and isolation are evaluated from data. The uncertainties associated with lepton identification and isolation are 1–2% for muons and electrons, and 6–7% for τ_h . Uncertainties on energy scales, 3% for τ_h and 1–2.5% for electrons, contribute to variation in the shape of the mass spectrum.

5 Results

Ten $\ell^+\ell^-\tau^+\tau^-$ candidates are observed in eight search channels, while 11.60 ± 0.54 (stat.) ± 1.62 (syst.) background events are expected. Table 1 compares the estimated number of background events to the number of events observed in the signal region. The distribution of the reconstructed invariant mass summed over all eight $\ell^+\ell^-\tau^+\tau^-$ decay channels is shown in Fig. 1. The shape of the background is taken from the MC simulation, with each component normalized to the corresponding estimated value from Table 1. The expected mass distributions for the SM Higgs boson with a mass of $m_H = 200$ GeV and 400 GeV are also shown in Fig. 1. The reconstructed masses are shifted with respect to the generated values by $\approx 30\%$ due to the undetected neutrinos in τ decays. As a result, the $H \rightarrow ZZ \rightarrow \ell^+\ell^-\tau^+\tau^-$ mass resolution is 10–15%, depending on the final state, and is almost independent of m_H .

The product of the acceptance and branching fraction for the individual τ -decay channels ranges between 0.01–0.02 for $m_H = 200$ GeV, and increases by a factor of three to four for $m_H = 400$ –450 GeV. This behaviour is expected. The final-state leptons produced in τ decays of more massive Higgs bosons have higher momenta than those from direct $Z \rightarrow \ell\ell$ production

Table 1: The estimated yields of ZZ and other background events obtained from data, as described in the text, are shown for each decay channel and are summed in the total background yield ("Total backgr."), and compared to the number of events observed in the signal region. The total uncertainty is the sum in quadrature of statistical and systematic uncertainties. The number of signal events expected for the SM Higgs boson with a mass of $m_H = 200 \text{ GeV}$ is also shown.

Decay channel	N_{ZZ}^{est}	Other backgrounds	Total backgr.	m_H 200 GeV	Observed
$\mu\mu\tau_h\tau_h$	0.79 ± 0.09	0.76 ± 0.31	1.55 ± 0.32	0.17	0
$ee\tau_h\tau_h$	0.75 ± 0.09	0.73 ± 0.32	1.48 ± 0.33	0.15	1
$ee\tau_e\tau_h$	1.12 ± 0.13	0.99 ± 0.34	2.11 ± 0.36	0.25	3
$\mu\mu\tau_e\tau_h$	1.20 ± 0.14	0.31 ± 0.29	1.51 ± 0.32	0.26	3
$\mu\mu\tau_\mu\tau_h$	1.08 ± 0.13	0.67 ± 0.36	1.75 ± 0.38	0.23	2
$ee\tau_\mu\tau_h$	0.94 ± 0.10	0.41 ± 0.16	1.35 ± 0.19	0.20	0
$ee\tau_e\tau_\mu$	0.51 ± 0.06	0.58 ± 0.42	1.09 ± 0.42	0.11	0
$\mu\mu\tau_e\tau_\mu$	0.58 ± 0.07	0.18 ± 0.18	0.76 ± 0.22	0.12	1
Total	6.97 ± 0.84	4.63 ± 1.49	11.60 ± 1.71	1.49	10

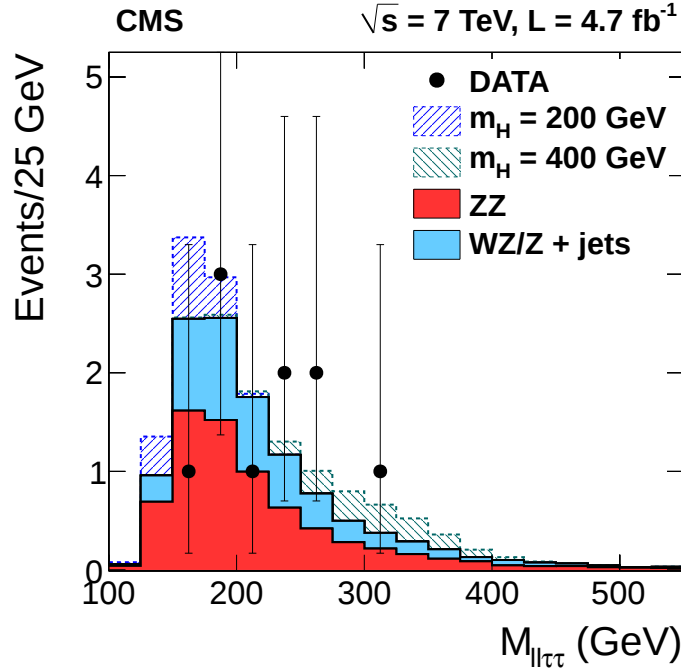


Figure 1: The four-lepton reconstructed mass summed for all $\ell^+\ell^-\tau^+\tau^-$ final states. The data corresponds to an integrated luminosity of 4.7 fb^{-1} . Points represent the data, shaded histograms represent the background and hashed histograms represent the signal expectations for two Higgs boson masses. The background shapes are taken from MC simulation and are normalized to the values obtained using control data samples, as described in the text.

and the selection requirements and the lepton reconstruction become more efficient at larger m_H . While the cross section decreases with increasing m_H , the expected number of Higgs boson events selected by this analysis in 4.7 fb^{-1} of pp collisions at 7 TeV is 1.4–1.5 in the range $200 < m_H < 400 \text{ GeV}$, and decreases rapidly at higher masses.

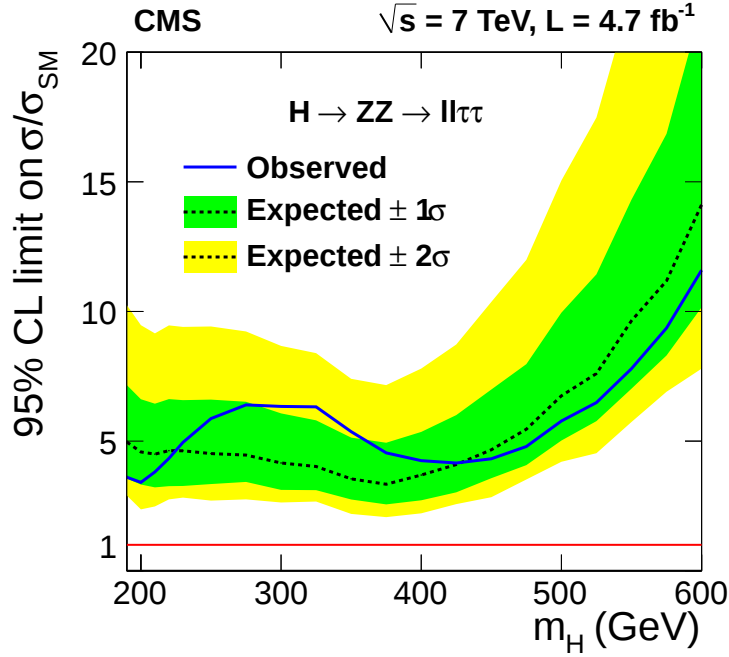


Figure 2: The expected and observed 95% CL upper limits on the product of the Higgs boson production cross section and decay branching fraction normalized to the SM expectation, denoted by $\sigma/\sigma_{\text{SM}}$, as a function of m_H . The one- and two-standard-deviation variations from the expected limit are also shown by the green and yellow bands.

In Fig. 2 the expected and observed upper limits at 95% CL on the product of the Higgs boson production cross section and decay branching fraction normalized to the SM expectation are presented as a function of m_H . The limits are calculated with the modified frequentist construction CL_s [58–60] based on the shape of the $\ell^+\ell^-\tau^+\tau^-$ invariant mass distributions by including all eight individual channels in the likelihood combination. The green and yellow bands represent the one- and two-standard-deviation variations from the expected limit. The systematic uncertainties are introduced in the form of nuisance parameters with log-normal probability density functions. The upper limit on the cross section is approximately a factor four to twelve larger than the SM Higgs boson production cross section in the range of $190 < m_H < 600 \text{ GeV}$.

6 Summary

A search for the standard model Higgs boson has been performed in the decay mode $H \rightarrow ZZ \rightarrow \ell^+\ell^-\tau^+\tau^-$ using CMS data corresponding to an integrated luminosity of 4.7 fb^{-1} . No evidence is found for a significant deviation from the background expectation. An upper limit four to twelve times larger than the predicted value is set at 95% confidence level for the product of the standard model Higgs boson production cross section and decay branching fraction in the mass range $190 < m_H < 600 \text{ GeV}$. This is the first Higgs boson search performed in the $H \rightarrow ZZ \rightarrow \ell^+\ell^-\tau^+\tau^-$ channel.

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