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Search for lepton-flavour-violating decays of the Higgs boson

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ABSTRACT

The first direct search for lepton-flavour-violating decays of the recently discovered Higgs boson (H) is described. The search is performed in the $H \to \mu\tau_e$ and $H \to \mu\tau_h$ channels, where τ_e and τ_h are tau leptons reconstructed in the electronic and hadronic decay channels, respectively. The data sample used in this search was collected in pp collisions at a centre-of-mass energy of $\sqrt{s} = 8$ TeV with the CMS experiment at the CERN LHC and corresponds to an integrated luminosity of 19.7 fb^{-1}. The sensitivity of the search is an order of magnitude better than the existing indirect limits. A slight excess of signal events with a significance of 2.4 standard deviations is observed. The p-value of this excess at $M_H = 125$ GeV is 0.010. The best fit branching fraction is $\mathcal{B}(H \to \mu\tau) = (0.84^{+0.39}_{-0.37})\%$. A constraint on the branching fraction, $\mathcal{B}(H \to \mu\tau) < 1.51\%$ at 95% confidence level is set. This limit is subsequently used to constrain the μ–τ Yukawa couplings to be less than 3.6×10^{-3}.

1. Introduction

The discovery of the Higgs boson (H) [1–3] has generated great interest in exploring its properties. In the standard model (SM), lepton-flavour-violating (LFV) decays are forbidden if the theory is to be renormalizable [4]. If this requirement is relaxed, so the theory is valid only to a finite mass scale, then LFV couplings may be introduced. LFV decays can occur naturally in models with more than one Higgs doublet without abandoning renormalizability [5]. They also arise in supersymmetric models [6–9], composite Higgs boson models [10,11], models with flavour symmetries [12], Randall–Sundrum models [13–15], and many others [16–23]. The presence of LFV couplings would allow $\mu \to e$, $\tau \to \mu$ and $\tau \to e$ transitions to proceed via a virtual Higgs boson [24,25]. The experimental limits on these have recently been translated into constraints on the branching fractions $\mathcal{B}(H \to e\mu, \mu\tau, e\tau)$ [4,26]. The $\mu \to e$ transition is strongly constrained by null search results for $\mu \to e\gamma$ [27], $\mathcal{B}(H \to \mu e) < \mathcal{O}(10^{-8})$. However, the constraints on $\tau \to \mu$ and $\tau \to e$ are much less stringent. These come from searches for $\tau \to \mu\gamma$ [28,29] and other rare τ decays [30], $\tau \to e\gamma$, μ and $eg - 2$ measurements [27]. Exclusion limits on the electron and muon electric dipole moments [31] also provide complementary constraints. These lead to the much less restrictive limits: $\mathcal{B}(H \to \mu\tau) < \mathcal{O}(10\%)$, $\mathcal{B}(H \to e\tau) < \mathcal{O}(10\%)$. The observation of the Higgs boson offers the possibility of sensitive direct searches for LFV Higgs boson decays. To date no dedicated searches have been performed. However, a theoretical reinterpretation of the ATLAS $H \to \tau\tau$ search results in terms of LFV decays by an independent group has been used to set limits at the 95% confidence level (CL) of $\mathcal{B}(H \to \mu\tau) < 13\%$, $\mathcal{B}(H \to e\tau) < 13\%$ [4].

This letter describes a search for a LFV decay of a Higgs boson with $M_H = 125$ GeV at the CMS experiment. The 2012 dataset collected at a centre-of-mass energy of $\sqrt{s} = 8$ TeV corresponding to an integrated luminosity of 19.7 fb^{-1} is used. The search is performed in two channels, $H \to \mu\tau_e$ and $H \to \mu\tau_h$, where τ_e and τ_h are tau leptons reconstructed in the electronic and hadronic decay channels, respectively. The signature is very similar to the SM $H \to \tau_\mu\tau_e$ and $H \to \tau_\mu\tau_h$ decays, where τ_μ is a tau lepton decaying muonically, which have been studied by CMS in Refs. [32,33] and ATLAS in Ref. [34], but with some significant kinematic differences. The μ comes promptly from the LFV H decay and tends to have a larger momentum than in the SM case. There is only one tau lepton so there are typically fewer neutrinos in the decay. They are highly Lorentz boosted and tend to be collinear with the visible τ decay products.

The two channels are divided into categories based on the number of jets in order to separate the different H boson production mechanisms. The signal sensitivity is enhanced by using different selection criteria for each category. The dominant production mechanism is gluon–gluon fusion but there is also a significant contribution from vector boson fusion which is enhanced by requiring jets to be present in the event. The dominant background in the $H \to \mu\tau_e$ channel is $Z \to \tau\tau$. Other much smaller

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backgrounds come from misidentified leptons in W + jets, QCD multijets and $t\bar{t}$ events. In the $H \to \mu\tau_h$ channel the dominant background arises from misidentified τ leptons in W + jets, QCD multijets and $t\bar{t}$ events. Less significant backgrounds come from $Z \to \tau\tau$ and Z + jets. The principal backgrounds are estimated using data. There is also a small background from SM H decays which is estimated with simulation. The presence or absence of a signal is established by fitting a mass distribution for signal and background using the asymptotic CL_s criterion [35,36]. A "blind" analysis was performed. The data in the signal region were not studied until the selection criteria had been fixed and the background estimate finalized.

2. Detector and data sets

A detailed description of the CMS detector, together with a description of the coordinate system used and the relevant kinematic variables, can be found in Ref. [37]. The momenta of charged particles are measured with a silicon pixel and strip tracker that covers the pseudorapidity range $|\eta| < 2.5$ and is inside a 3.8 T axial magnetic field. Surrounding the tracker are a lead tungstate crystal electromagnetic calorimeter (ECAL) and a brass/scintillator hadron calorimeter, both consisting of a barrel assembly and two endcaps that extend to a pseudorapidity range of $|\eta| < 3.0$. A steel/quartz-fiber Cherenkov forward detector extends the calorimetric coverage to $|\eta| < 5.0$. The outermost component of the CMS detector is the muon system, consisting of gas-ionization detectors placed in the steel flux-return yoke of the magnet to measure the momenta of muons traversing the detector. The two-level CMS trigger system selects events of interest for permanent storage. The first trigger level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events in less than 3.2 μs. The high-level trigger software algorithms, executed on a farm of commercial processors, further reduce the event rate using information from all detector subsystems.

The $H \to \mu\tau_h$ channel selection begins by requiring a single μ trigger with a transverse momentum threshold $p_T^{\mu} > 24$ GeV in the pseudorapidity range $|\eta| < 2.1$, while the $H \to \mu\tau_e$ channel requires a μ–e trigger with p_T thresholds of 17 GeV ($|\eta| < 2.4$) for the μ and 8 GeV ($|\eta| < 2.5$) for the e. Loose e and μ identification criteria are applied at the trigger level. The leptons are also required to be isolated from other tracks and calorimeter energy deposits to maintain an acceptable trigger rate.

Simulated samples of signal and background events are produced using various Monte Carlo (MC) event generators, with the CMS detector response modeled with GEANT4 [38]. Higgs bosons are produced in proton–proton collisions predominantly by gluon–gluon fusion, but also by vector boson fusion and in association with a W or Z boson. It is assumed that the rate of new decays of the H are sufficiently small that the narrow width approximation can be used. The LFV H decay samples are produced with PYTHIA 8.175 [39]. The background event samples with a SM H are generated by POWHEG 1.0 [40–44] with the τ decays modeled by TAUOLA [45]. The MADGRAPH 5.1 [46] generator is used for Z + jets, W + jets, $t\bar{t}$, and diboson production, and POWHEG for single top-quark production. The POWHEG and MADGRAPH generators are interfaced with PYTHIA for parton shower and fragmentation.

3. Event reconstruction

A particle-flow (PF) algorithm [47,48] combines the information from all CMS sub-detectors to identify and reconstruct the individual particles emerging from all vertices: charged hadrons, neutral hadrons, photons, muons, and electrons. These particles are then used to reconstruct jets, hadronic τ decays, and to quantify the isolation of leptons and photons. The missing transverse energy vector is the negative vector sum of all particle transverse momenta and its magnitude is referred to as E_T^{miss}. The variable $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ is used to measure the separation between reconstructed objects in the detector, where ϕ is the azimuthal angle (in radians) of the trajectory of the object in the plane transverse to the direction of the proton beams.

The large number of proton interactions occurring per LHC bunch crossing (pileup), with an average of 21 in 2012, makes the identification of the vertex corresponding to the hard-scattering process nontrivial. This affects most of the object reconstruction algorithms: jets, lepton isolation, etc. The tracking system is able to separate collision vertices as close as 0.5 mm along the beam direction [49]. For each vertex, the sum of the p_T^2 of all tracks associated with the vertex is computed. The vertex for which this quantity is the largest is assumed to correspond to the hard-scattering process, and is referred to as the primary vertex in the event reconstruction.

Muons are reconstructed using two algorithms [50]: one in which tracks in the silicon tracker are matched to signals in the muon detectors, and another in which a global track fit is performed, seeded by signals in the muon systems. The muon candidates used in the analysis are required to be successfully reconstructed by both algorithms. Further identification criteria are imposed on the muon candidates to reduce the fraction of tracks misidentified as muons. These include the number of measurements in the tracker and in the muon systems, the fit quality of the global muon track and its consistency with the primary vertex.

Electron reconstruction requires the matching of an energy cluster in the ECAL with a track in the silicon tracker [51,52]. Identification criteria based on the ECAL shower shape, matching between the track and the ECAL cluster, and consistency with the primary vertex are imposed. Electron identification relies on a multivariate technique that combines observables sensitive to the amount of bremsstrahlung along the electron trajectory, the geometrical and momentum matching between the electron trajectory and associated clusters, as well as shower-shape observables. Additional requirements are imposed to remove electrons produced by photon conversions.

Jets are reconstructed from all the PF objects using the anti-k_T jet clustering algorithm [53] implemented in FASTJET [54], with a distance parameter of 0.5. The jet energy is corrected for the contribution of particles created in pileup interactions and in the underlying event. Particles from different pileup vertices can be clustered into a pileup jet, or significantly overlap a jet from the primary vertex below the p_T threshold applied in the analysis. Such jets are identified and removed [55].

Hadronically decaying τ leptons are reconstructed and identified using the hadron plus strips (HPS) algorithm [56] which targets the main decay modes by selecting PF candidates with one charged hadron and up to two neutral pions, or with three charged hadrons. A photon from a neutral-pion decay can convert in the tracker material into an electron and a positron, which can then radiate bremsstrahlung photons. These particles give rise to several ECAL energy deposits at the same η value and separated in azimuthal angle, and are reconstructed as several photons by the PF algorithm. To increase the acceptance for such converted photons, the neutral pions are identified by clustering the reconstructed photons in narrow strips along the azimuthal direction.

4. Event selection

The event selection consists of three steps. First, a loose selection defining the basic signature is applied. The sample is then divided into categories, according to the number of jets in the