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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 $\mathrm{H} \to \mu\tau_\mathrm{e}$ and $\mathrm{H} \to \mu\tau_\mathrm{h}$ 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 $\sqrt{s} = 8\,\mathrm{TeV}$ with the CMS experiment at the CERN LHC and corresponds to an integrated luminosity of $19.7\,\mathrm{fb}^{-1}$. 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 $M_\mathrm{H} = 125\,\mathrm{GeV}$ is 0.010. The best fit branching fraction is $\mathcal{B}(\mathrm{H} \to \mu\tau) = (0.84^{+0.39}_{-0.37})\%$. A constraint on the branching fraction, $\mathcal{B}(\mathrm{H} \to \mu\tau) < 1.51\%$ 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}.

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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 [6–8], composite Higgs boson models [9, 10], models with flavour symmetries [11], Randall–Sundrum models [12–14], and many others [15–20]. The presence of LFV couplings would allow $\mu \to \mathrm{e}$, $\tau \to \mu$ and $\tau \to \mathrm{e}$ transitions to proceed via a virtual Higgs boson [21, 22]. The experimental limits on these have recently been translated into constraints on the branching fractions $\mathcal{B}(\mathrm{H} \to \mathrm{e}\mu, \mu\tau, \mathrm{e}\tau)$ [4, 23]. The $\mu \to \mathrm{e}$ transition is strongly constrained by null search results for $\mu \to \mathrm{e}\gamma$ [24], $\mathcal{B}(\mathrm{H} \to \mu\mathrm{e}) < \mathcal{O}(10^{-8})$. However, the constraints on $\tau \to \mu$ and $\tau \to \mathrm{e}$ are much less stringent. These come from searches for $\tau \to \mu\gamma$ [25, 26] and other rare τ decays [27], $\tau \to \mathrm{e}\gamma$, μ and e $g-2$ measurements [24]. Exclusion limits on the electron and muon electric dipole moments [28] also provide complementary constraints. These lead to the much less restrictive limits: $\mathcal{B}(\mathrm{H} \to \mu\tau) < \mathcal{O}(10\%)$, $\mathcal{B}(\mathrm{H} \to \mathrm{e}\tau) < \mathcal{O}(10\%)$. 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 $\mathrm{H} \to \tau\tau$ search results in terms of LFV decays by an independent group has been used to set limits at the 95% confidence level (CL) of $\mathcal{B}(\mathrm{H} \to \mu\tau) < 13\%$, $\mathcal{B}(\mathrm{H} \to \mathrm{e}\tau) < 13\%$ [4].

This letter describes a search for a LFV decay of a Higgs boson with $M_{\mathrm{H}} = 125\,\mathrm{GeV}$ at the CMS experiment. The 2012 dataset collected at a centre-of-mass energy of $\sqrt{s} = 8\,\mathrm{TeV}$ corresponding to an integrated luminosity of 19.7 fb^{-1} is used. The search is performed in two channels, $\mathrm{H} \to \mu\tau_{\mathrm{e}}$ and $\mathrm{H} \to \mu\tau_{\mathrm{h}}$, 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 $\mathrm{H} \to \tau_{\mu}\tau_{\mathrm{e}}$ and $\mathrm{H} \to \tau_{\mu}\tau_{\mathrm{h}}$ decays, which have been studied by CMS in Refs. [29, 30], 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. In addition, since the neutrinos in the decay arise from one τ which is highly Lorentz boosted, they 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 production mechanisms. 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 $\mathrm{H} \to \mu\tau_{\mathrm{e}}$ channel is $\mathrm{Z} \to \tau\tau$. Other much smaller backgrounds come from misidentified leptons in W+jets, QCD multijets and $\mathrm{t\bar{t}}$ events. In the $\mathrm{H} \to \mu\tau_{\mathrm{h}}$ channel the dominant background arises from misidentified τ leptons in W+jets, QCD multijets and $\mathrm{t\bar{t}}$ events. Less significant backgrounds come from $\mathrm{Z} \to \tau\tau$ 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 $\mathrm{CL_s}$ criterion [31, 32]. 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. [33]. 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 $\mathrm{H} \to \mu\tau_{\mathrm{h}}$ channel selection begins by requiring a single μ trigger with a transverse momentum threshold $p_{\mathrm{T}}^{\mu} > 24\,\mathrm{GeV}$ in the pseudorapidity range $|\eta| < 2.1$, while the $\mathrm{H} \to \mu\tau_{\mathrm{e}}$ 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 [34]. 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 [35]. The background event samples with a SM H are generated by POWHEG 1.0 [36–40] with the τ decays modelled by TAUOLA [41]. The MADGRAPH 5.1 [42] generator is used for Z+jets, W+jets, $\mathrm{t\bar{t}}$, 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 [43, 44] 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 $E_{\mathrm{T}}^{\mathrm{miss}}$. 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 [45]. 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 [46]: 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 [47, 48]. 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 [49] implemented in FASTJET [50], 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. The jet energy scale uncertainty is extracted from a comparison between the observed data and the simulation for γ+jets, Z+jets, and dijet events [51]. 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 [52].

Hadronically decaying τ leptons are reconstructed and identified using the hadron plus strips (HPS) algorithm [53] 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. Finally, requirements are placed on a set of kinematic variables designed to suppress the backgrounds.

The loose selection for the $\mathrm{H} \to \mu\tau_{\mathrm{e}}$ sample requires an isolated μ ($p_{\mathrm{T}} > 25\,\mathrm{GeV}$, $|\eta| < 2.1$) and an isolated e ($p_{\mathrm{T}} > 10\,\mathrm{GeV}$, $|\eta| < 2.3$) of opposite charge lying within a region of the detector that allows good identification. The e and μ are required to be separated by $\Delta R > 0.1$. The $\mathrm{H} \to \mu\tau_{\mathrm{h}}$ sample requires an isolated μ ($p_{\mathrm{T}} > 30\,\mathrm{GeV}$, $|\eta| < 2.1$) and an isolated hadronic τ ($p_{\mathrm{T}} > 30\,\mathrm{GeV}$, $|\eta| < 2.3$) of opposite charge. Leptons are also required to be isolated from any jet in the event with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ by $\Delta R > 0.4$ and to have an impact parameter consistent with the primary vertex.

The events are then divided into categories within each sample according to the number of jets in the event. Jets are required to pass identification criteria [52], have $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and lie within the range $|\eta| < 4.7$. The zero jet category contains signal events produced by gluon-gluon fusion. The one-jet category contains signal events produced by gluon-gluon fusion and events produced in association with a W or Z boson decaying hadronically. The two jet category is enriched with signal events produced by vector boson fusion.

Table 1: Selection criteria for the kinematic variables after the loose selection.

Variable	$\mathrm{H} \to \mu\tau_{\mathrm{e}}$			$\mathrm{H} \to \mu\tau_{\mathrm{h}}$		
[GeV]	0-jet	1-jet	2-jet	0-jet	1-jet	2-jet
$p_{\mathrm{T}}^{\mu} >$	50	45	25	45	35	30
$p_{\mathrm{T}}^{\mathrm{e}} >$	10	10	10	—	—	—
$p_{\mathrm{T}}^{\tau} >$	—	—	—	35	40	40
$M_{\mathrm{T}}^{\mathrm{e}} <$	65	65	25	—	—	—
$M_{\mathrm{T}}^{\mu} >$	50	40	15	—	—	—
$M_{\mathrm{T}}^{\tau} <$	—	—	—	50	35	35
[radians]						
$\Delta\phi_{\vec{p}_{\mathrm{T}}^{\mu}-\vec{p}_{\mathrm{T}}^{\tau_{\mathrm{h}}}} >$	—	—	—	2.7	—	—
$\Delta\phi_{\vec{p}_{\mathrm{T}}^{\mathrm{e}}-\vec{E}_{\mathrm{T}}^{\mathrm{miss}}} <$	0.5	0.5	0.3	—	—	—
$\Delta\phi_{\vec{p}_{\mathrm{T}}^{\mathrm{e}}-\vec{p}_{\mathrm{T}}^{\mu}} >$	2.7	1.0	—	—	—	—

The signal variable is the collinear mass, M_{col}, which provides an estimator of the reconstructed H mass using the observed decay products. This is constructed using the collinear approximation [54] which is based on the observation that since the mass of the H is much greater than the mass of the τ, the τ decay products are highly Lorentz boosted in the direction of the τ. The neutrino momenta can be approximated to be in the same direction as the other visible decay products of the τ and the component of the missing transverse energy in the direction of the visible τ decay products is used to estimate the transverse component of the neutrino momentum. Figure 1 shows M_{col} for the signal and background compared to data for each of the categories in each channel after the loose selection. The signal simulation for $\mathcal{B}(\mathrm{H} \to \mu\tau) = 100\%$ is shown. The principal backgrounds are estimated with data using techniques described in Section 5. There is good agreement between data and the background estimation. The agreement is similar in all of the kinematic variables that are subsequently used to suppress backgrounds. The analysis is performed "blinded" in the region $100 < M_{\mathrm{col}} < 150\,\mathrm{GeV}$.

Next, a set of kinematic variables is defined and the criteria for selection are determined by optimizing for $\mathrm{S}/\sqrt{\mathrm{S}+\mathrm{B}}$ where S and B are the expected signal and background event yields in the mass window $100 < M_{\mathrm{col}} < 150\,\mathrm{GeV}$. The signal strength is set according to the SM H production cross section at $M_{\mathrm{H}} = 125\,\mathrm{GeV}$ with $\mathcal{B}(\mathrm{H} \to \mu\tau) = 10\%$. This value for the LFV H branching fraction is chosen because it corresponds to the limit from indirect measurements as described in Ref. [4]. The optimization was also evaluated assuming $\mathcal{B}(\mathrm{H} \to \mu\tau) = 1\%$ and negligible change in the optimal values of selection criteria was observed. The criteria for each category, and in each channel, are given in Table 1. The variables used are the lepton transverse momenta p_{T}^{ℓ} with $\ell = \tau, \mu, \mathrm{e}$; azimuthal angles between the leptons $\Delta\phi_{\vec{p}_{\mathrm{T}}^{\ell_1}-\vec{p}_{\mathrm{T}}^{\ell_2}}$; azimuthal angle $\Delta\phi_{\vec{p}_{\mathrm{T}}^{\ell}-\vec{E}_{\mathrm{T}}^{\mathrm{miss}}}$; the transverse mass $M_{\mathrm{T}}^{\ell} = \sqrt{2p_{\mathrm{T}}^{\ell}E_{\mathrm{T}}^{\mathrm{miss}}(1-\cos\Delta\phi_{\vec{p}_{\mathrm{T}}^{\ell}-\vec{E}_{\mathrm{T}}^{\mathrm{miss}}})}$. Events in the vector boson fusion category are required to have two jets separated by a pseudorapidity gap ($|\Delta\eta| > 3.5$) and to have a dijet invariant mass greater than $550\,\mathrm{GeV}$. In the $\mathrm{H} \to \mu\tau_{\mathrm{e}}$ channel

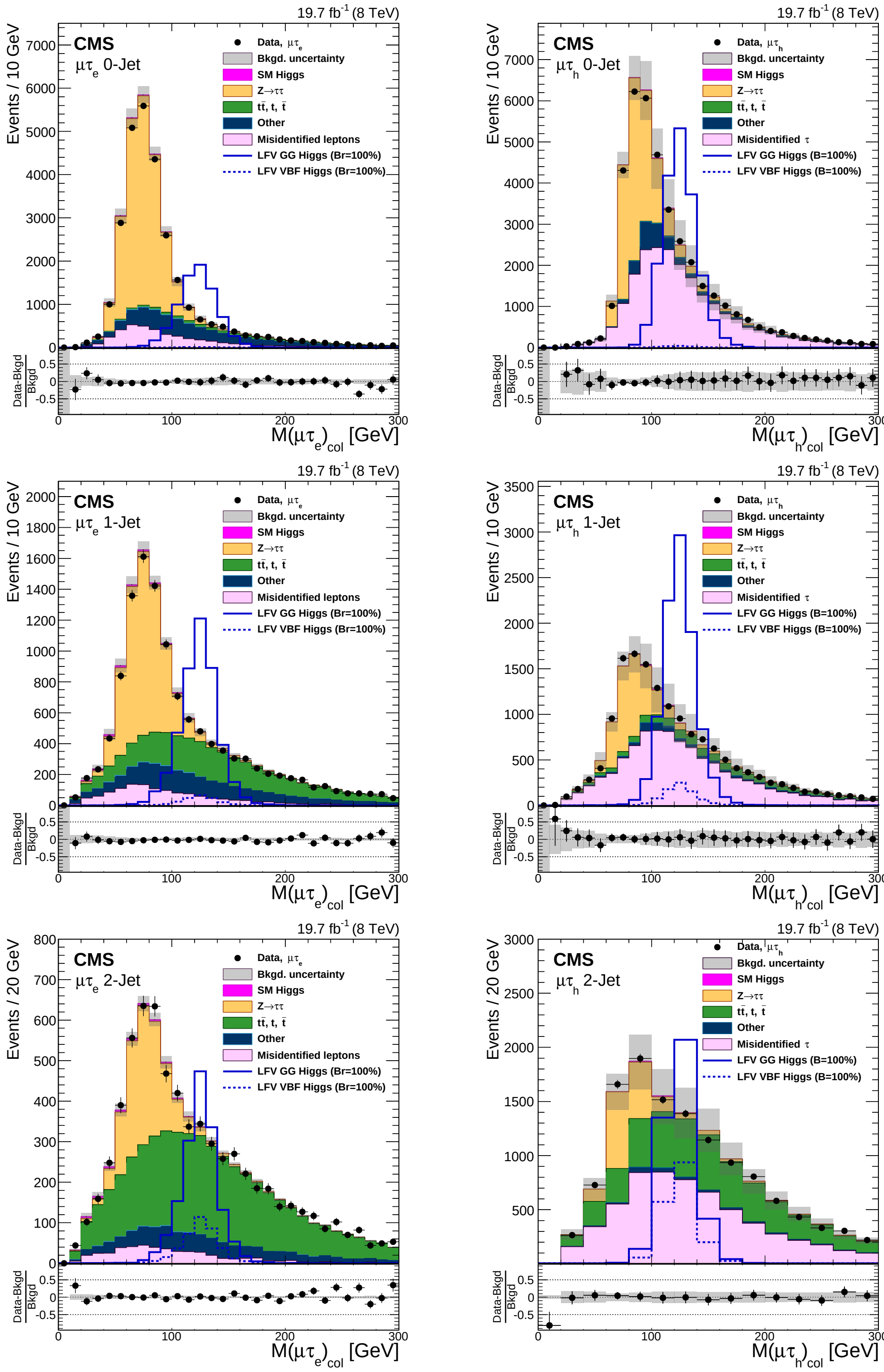

Figure 1: Distributions of the collinear mass M_{col} for signal ($\mathcal{B}(\mathrm{H} \to \mu\tau) = 100\%$ for clarity) and background after the loose selection requirements for the LFV $\mathrm{H} \to \mu\tau$ candidates for the different channels and categories compared to data. The shaded grey bands indicate the total uncertainty. The bottom panel in each plot shows the fractional difference between the observed data and the total estimated background. Top left: $\mathrm{H} \to \mu\tau_{\mathrm{e}}$ 0-jet; top right: $\mathrm{H} \to \mu\tau_{\mathrm{h}}$ 0-jet; middle left: $\mathrm{H} \to \mu\tau_{\mathrm{e}}$ 1-jet; middle right: $\mathrm{H} \to \mu\tau_{\mathrm{h}}$ 1-jet; bottom left: $\mathrm{H} \to \mu\tau_{\mathrm{e}}$ 2-jet; bottom right $\mathrm{H} \to \mu\tau_{\mathrm{h}}$ 2-jet.

events in which at least one of the jets is identified as coming from a b-quark decay are vetoed using the combined secondary-vertex b-tagging algorithm [55], to suppress backgrounds from top quark decays.

5 Backgrounds

The dominant backgrounds are estimated with data while less significant backgrounds are estimated using simulation. The largest backgrounds come from $Z \to \tau\tau$ and from misidentified leptons in W+jets and QCD multijets.

5.1 $Z \to \tau\tau$

The $Z \to \tau\tau$ background is estimated using an embedding technique [30, 56] as follows. A sample of $Z \to \mu\mu$ events is taken from data using a loose selection. The μ are then replaced with PF particles resulting from the reconstruction of simulated τ decays. Thus, the key features of the event topology such as the jets, missing transverse energy and underlying event are taken directly from data with only the τ decays being simulated. The normalization of the sample is from the simulation. The technique is validated by comparing identification efficiencies estimated with embedded decays to those from simulated $Z \to \tau\tau$ decays.

5.2 Misidentified leptons

Leptons can arise from misidentified PF objects in W+jets and QCD multijets. This background is estimated with data. A sample with similar kinematic properties to the signal sample but enriched in W+jets and QCD multijets is defined. Then the probability for PF objects to be misidentified as leptons is measured in an independent data set, and this probability is applied to the enriched sample to compute the misidentified lepton background in the signal sample. The technique is shown schematically in Table 2 in which four regions are defined including the signal and enriched regions and two control regions used for validation of the technique. It is employed slightly differently in the $H \to \mu\tau_e$ and $H \to \mu\tau_h$ channels. The lepton isolation requirements used to define the enriched regions in each channel are slightly different.

In the $H \to \mu\tau_e$ channel, region I is the signal region in which an isolated μ and an isolated e are required. Region III is a data sample in which all the analysis selection criteria are applied except that one of the leptons is required to be not-isolated, so that there are two components: isolated μ plus not-isolated e events, and also isolated e plus not-isolated μ events. Regions II and IV are data samples formed with the same selection criteria as regions I and III respectively but with like-sign rather than opposite sign leptons. The sample in region III is dominated

Table 2: Schematic to illustrate the application of the method used to estimate the misidentified lepton (ℓ) background. Samples are defined by the charge of the two leptons and by the isolation requirements on each. Charged conjugates are assumed.

Region I	**Region II**
ℓ_1^+(isolated)	ℓ_1^+(isolated)
ℓ_2^-(isolated)	ℓ_2^+(isolated)
Region III	**Region IV**
ℓ_1^+(isolated)	ℓ_1^+(isolated)
ℓ_2^-(not-isolated)	ℓ_2^+(not-isolated)

by W+jets and QCD multijets but with small contributions from WW, ZZ and WZ that are subtracted using simulation. The misidentified μ background in region I is then estimated by multiplying the event yield in region III by a factor $f_\mu \cdot \epsilon_{\text{trigger}}$, where f_μ is the ratio of not-isolated to isolated μ's. It is computed in an independent data sample $\mathrm{Z} \to \mu\mu + X$, where X is an object identified as a μ, in bins of p_{T} and η. The $\mathrm{Z} \to \mu\mu + X$ sample is corrected for contributions from WW, ZZ and WZ using simulated samples. A correction $\epsilon_{\text{trigger}}$ is made to account for the difference in trigger efficiency for selecting the isolated e plus not-isolated μ versus selecting the isolated e plus isolated μ. The misidentified e background is computed in exactly the same way. The technique is validated by using a like-sign rather than opposite-sign lepton data sample as shown schematically in Table 2. In Fig. 2(left) the observed data yield in region II is compared to the estimate from scaling the region IV sample by the measured misidentification rates. The region II sample is dominated by misidentified leptons but also includes small contributions of true leptons arising from vector boson decays, estimated with simulated samples.

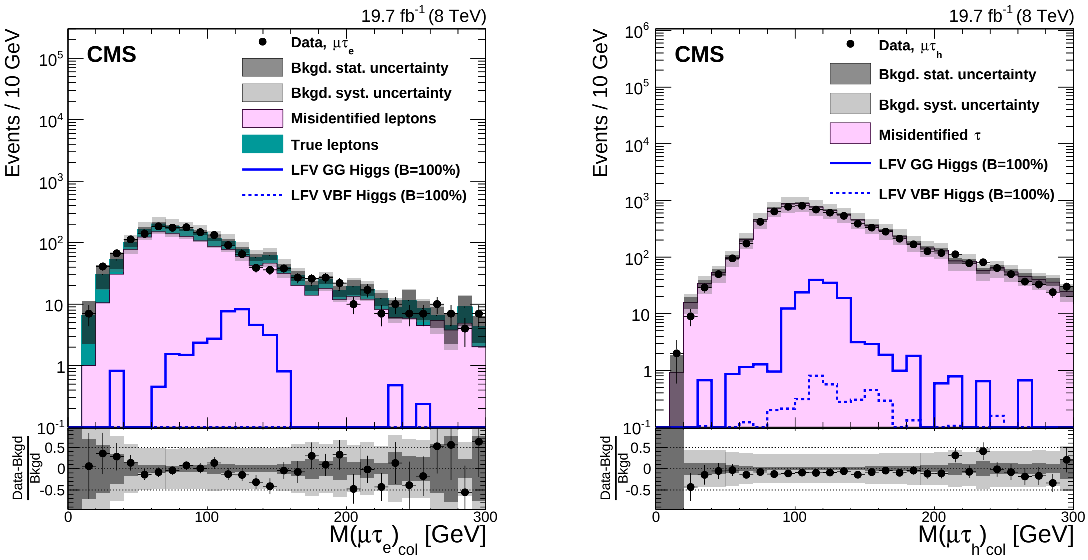

Figure 2: Distributions of M_{col} for region II compared to the estimate from scaling the region IV sample by the measured misidentification rates. The bottom panel in each plot shows the fractional difference between the observed data and the estimate. Left: $\mathrm{H} \to \mu\tau_{\mathrm{e}}$. Right: $\mathrm{H} \to \mu\tau_{\mathrm{h}}$.

In the $\mathrm{H} \to \mu\tau_{\mathrm{h}}$ channel, the τ_{h} candidate can come from a misidentified jet with a number of sources, predominantly W+jets and QCD multijets, but also $\mathrm{Z} \to \mu\mu$+jets and $\mathrm{t\bar{t}}$. In this case the enriched background regions are defined with τ_h candidates that pass a looser isolation requirement, but do not pass the signal isolation requirement. The misidentification rate $f_{\tau_{\mathrm{h}}}$ is then defined as the fraction of τ_{h} candidates with the looser isolation that also pass the signal isolation requirement. It is measured in observed $\mathrm{Z} \to \mu\mu + X$ events, where X is an object identified as a τ_{h}. The misidentification rate measured in $\mathrm{Z} \to \mu\mu + X$ data is checked by comparing to that measured in $\mathrm{Z} \to \mu\mu + X$ simulation and found to be in good agreement. The misidentified background in the signal region (region I) is estimated by multiplying the event yield in region III by a factor $f_{\tau_{\mathrm{h}}}/(1 - f_{\tau_{\mathrm{h}}})$. The procedure is validated with like-sign $\mu\tau$ events in the same way as for the $\mathrm{H} \to \mu\tau_{\mathrm{e}}$ channel above. Figure 2(right) shows the data in region II compared to the estimate from scaling region IV by the misidentification rates.

The method assumes that the misidentification rate in $\mathrm{Z} \to \mu\mu + X$ events is the same as for W+jets and QCD processes. To test this assumption the misidentification rates are measured in a QCD jet data control sample. They are found to be consistent. Finally as a cross-check

Table 3: Systematic uncertainties in %. All uncertainties are treated as correlated between the categories, except where there are two numbers. In this case the number denoted with * is treated as uncorrelated between categories and the total uncertainty is the sum in quadrature of the two numbers.

Systematic uncertainty	$H \to \mu\tau_e$			$H \to \mu\tau_h$		
	0-Jet	1-Jet	2-Jets	0-Jet	1-Jet	2-Jets
electron trigger/ID/isolation	3	3	3	—	—	—
muon trigger/ID/isolation	2	2	2	2	2	2
hadronic tau efficiency	—	—	—	9	9	9
luminosity	2.6	2.6	2.6	2.6	2.6	2.6
$Z \to \tau\tau$ background	3+3*	3+5*	3+10*	3+5*	3+5*	3+10*
$Z \to \mu\mu$, ee background	30	30	30	30	30	30
misidentified μ, e background	40	40	40	—	—	—
misidentified τ_h background	—	—	—	30+10*	30	30
WW, ZZ+jets background	15	15	15	15	15	65
$t\bar{t}$ background	10	10	10+10*	10	10	10+33*
$W + \gamma$ background	100	100	100	—	—	—
b-tagging veto	3	3	3	—	—	—
single top production background	10	10	10	10	10	10

the study has been performed also as a function of the number of jets in the event and similar agreement is found.

5.3 Other backgrounds

The SM H decays in the $H \to \tau\tau$ channel provide a small background that is estimated with simulation. This background is suppressed by the kinematic selection criteria and peaks below 125 GeV. The W leptonic decay from $t\bar{t}$ produces opposite sign dileptons and E_T^{miss}. This background is estimated with simulated $t\bar{t}$ events using the shape of the M_{col} distribution from simulation and a data control region for normalization. The control region is the 2-jet selection but with the additional requirement that at least one of the jets is b-tagged in order to enhance the $t\bar{t}$ contribution. Other smaller backgrounds come from WW, ZZ+jets, $W\gamma$+jets and single top production. Each of these is estimated with simulation.

6 Systematic uncertainties

To set upper bounds on the signal strength, or determine a signal significance, we use the CL_s method [31, 32]. A binned likelihood is used, based on the distributions of M_{col} for the signal and the various background sources. Systematic uncertainties are represented by nuisance parameters, some of which only affect the background and signal normalizations, while others affect the shape and/or normalization of the M_{col} distributions.

6.1 Normalization uncertainties

The uncertainties are summarized in Tables 3 and 4. The uncertainties in the e and μ selection (trigger, identification and isolation) are estimated using the "tag and probe" technique in $Z \to$ ee, $\mu\mu$ data [56]. The hadronic τ efficiency is estimated using the "tag and probe" technique in $Z \to \tau\tau$ data [53]. The uncertainty in the $Z \to \tau\tau$ background comes predominantly from the uncertainty in the τ efficiency. The uncertainties in the estimation of the misidentified lepton rate come from the difference in rates measured in different data samples (QCD multijets and

W+jets). The uncertainty in the production cross section of the backgrounds that have been estimated by simulation is also included.

There are several uncertainties that arise from the theoretical uncertainty in the H production cross section, which differ for each production mechanism contribution within each category. They are given in Table 4. These affect the LFV H and the SM H background equally, and are treated as 100% correlated. The parton distribution function (PDF) uncertainty is evaluated by comparing the yields in each category, when spanning the parameter range of a number of different independent PDF sets including CT10 [57], MSTW [58], NNPDF [59] as recommended by PDF4LHC [60]. The scale uncertainty is estimated by varying the renormalization, μ_R, and factorization scale, μ_F, up and down by one half or two times the nominal scale ($\mu_R = \mu_F = M_{\mathrm{H}}/2$) under the constraint $0.5 < \mu_F/\mu_R < 2$. The underlying event and parton shower uncertainty is estimated by using two different PYTHIA tunes, AUET2 and Z2*. Anticorrelations arise due to migration of events between the categories and are expressed as negative numbers.

Table 4: Theoretical uncertainties in % for Higgs boson production. Anticorrelations arise due to migration of events between the categories and are expressed as negative numbers.

Systematic uncertainty	Gluon-Gluon Fusion			Vector Boson Fusion		
	0-Jets	1-Jets	2-Jets	0-Jet	1-Jet	2-Jets
parton density function	+9.7	+9.7	+9.7	+3.6	+3.6	+3.6
renormalization/factorization scale	+8	+10	−30	+4	+1.5	+2
underlying event/parton shower	+4	−5	−10	+10	<1	−1

6.2 M_{col} shape uncertainties

The systematic uncertainties that lead to a change in the shape of the M_{col} distribution are summarized in Table 5. In the embedded $\mathrm{Z} \to \tau\tau$ M_{col} distribution, used to estimate the $\mathrm{Z} \to \tau\tau$ background, a 1% shift has been observed with respect to $\mathrm{Z} \to \tau\tau$ simulations by comparing the means of both distributions. This occurs only in the $\mathrm{H} \to \mu\tau_{\mathrm{e}}$ channel. The M_{col} distribution has been corrected for this effect and a 100% uncertainty on this shift is used as a systematic uncertainty for the possible bias. The jet energy scale has been studied extensively and a standard prescription for corrections [51] is used in all CMS analyses. The overall scale is set using γ+jets events and the most significant uncertainty is in the photon energy scale. A number of other uncertainties such as jet fragmentation modeling, single pion response and uncertainties in the pileup corrections are also included. The jet energy scale uncertainties (3–7%) are applied as a function of p_{T} and η, including all correlations, to all jets in the event, propagated to the missing energy, and the resultant M_{col} distribution is used in the fit. There is also an additional uncertainty added to account for the unclustered energy scale uncertainty. The unclustered energy comes from jets below 10 GeV and PF candidates not within jets. It is also propagated to the missing transverse energy. These effects cause a shift of the M_{col} distribution. The τ energy scale is estimated by comparing $\mathrm{Z} \to \tau\tau$ events in data and simulation. An uncertainty of 3% is derived from this comparison. The uncertainty is applied by shifting the p_{T} of the τ candidates in the event and the resultant M_{col} distribution is used in the fit. Finally, the M_{col} distributions

Table 5: Systematic uncertainties in % for the shape of the signal and background templates.

Systematic uncertainty	$\mathrm{H} \to \mu\tau_{\mathrm{e}}$	$\mathrm{H} \to \mu\tau_{\mathrm{h}}$
hadronic tau energy scale	—	3
jet energy scale	3–7	3–7
unclustered energy scale	10	10
$\mathrm{Z} \to \tau\tau$ bias	100	—

used in the fit have a statistical uncertainty in each mass bin that is included as an uncertainty which is uncorrelated between the bins.

Potential uncertainties in the shape of the misidentified lepton backgrounds have also been considered. In the $H \to \mu\tau_e$ channel the misidentified lepton rates f_μ, f_e are measured and applied in bins of lepton p_T and η. These rates are all adjusted up or down by one standard deviation (σ) and the differences in the shape of the resultant M_{col} distributions are then used as nuisance parameters in the fit. In the $H \to \mu\tau_h$ channel the τ misidentification rate f_τ is found to be approximately flat in p_T and η. To estimate the systematic uncertainty the p_T distribution of f_τ is fit with a linear function and the rate recomputed from the fitted slope and intercept. The modified M_{col} distribution that results from the recomputed background is then used to evaluate the systematic uncertainty.

7 Results

The M_{col} distributions after fitting for signal and background are shown in Fig. 3 and the event yields in the mass range $100 < M_{col} < 150\,\text{GeV}$ are shown in Table 6. The different channels and categories are used to set a 95% CL upper limit on the branching fraction of LFV H decay in the $\mu\tau$ channel, $\mathcal{B}(H \to \mu\tau)$.

Table 6: Event yields in the signal region, $100 < M_{col} < 150\,\text{GeV}$ after fitting for signal and background. The expected contributions are normalized to an integrated luminosity of $19.7\,\text{fb}^{-1}$. The LFV Higgs boson signal is the expected yield for $B(H \to \mu\tau) = 0.84\%$ with the SM Higgs boson cross section.

Sample	$H \to \mu\tau_h$			$H \to \mu\tau_e$		
	0-Jet	1-Jet	2-Jets	0-Jet	1-Jet	2-Jets
misidentified leptons	1770 ± 530	377 ± 114	1.8 ± 1.0	42 ± 17	16 ± 7	1.1 ± 0.7
$Z \to \tau\tau$	187 ± 10	59 ± 4	0.4 ± 0.2	65 ± 3	39 ± 2	1.3 ± 0.2
ZZ, WW	46 ± 8	15 ± 3	0.2 ± 0.2	41 ± 7	22 ± 4	0.7 ± 0.2
$W\gamma$	—	—	—	2 ± 2	2 ± 2	—
$Z \to ee$ or $\mu\mu$	110 ± 23	20 ± 7	0.1 ± 0.1	1.6 ± 0.7	1.8 ± 0.8	—
$t\bar{t}$	2.2 ± 0.6	24 ± 3	0.9 ± 0.5	4.8 ± 0.7	30 ± 3	1.8 ± 0.4
$t\bar{t}$	2.2 ± 1.1	13 ± 3	0.5 ± 0.5	1.9 ± 0.2	6.8 ± 0.8	0.2 ± 0.1
SM H background	7.1 ± 1.3	5.3 ± 0.8	1.6 ± 0.5	1.9 ± 0.3	1.6 ± 0.2	0.6 ± 0.1
sum of backgrounds	2125 ± 530	513 ± 114	5.4 ± 1.4	160 ± 19	118 ± 9	5.6 ± 0.9
LFV Higgs boson signal	66 ± 18	30 ± 8	2.9 ± 1.1	23 ± 6	13 ± 3	1.2 ± 0.3
data	2147	511	10	180	128	6

The observed and the median expected 95% CL upper limits for the H mass at 125 GeV are given for each category in Table 7. Combining all the channels, an expected upper limit of $\mathcal{B}(H \to \mu\tau) < (0.75 \pm 0.38)\%$ is obtained. The observed upper limit is $\mathcal{B}(H \to \mu\tau) < 1.51\%$ which is above the expected limit due to an excess of the observed number of events above the background prediction. The fit can then be used to estimate the branching fraction if this excess were to be interpreted as a signal. The best fit values for the branching fractions are given in Table 7. The limits and best fit branching fractions are also summarized graphically in Fig. 4. The combined categories give a best fit of $\mathcal{B}(H \to \mu\tau) = (0.84^{+0.39}_{-0.37})\%$. The combined excess is 2.4 standard deviations which corresponds to a p-value of 0.010 at $M_H = 125\,\text{GeV}$. The observed and expected M_{col} distributions combined for all channels and categories are shown in Fig. 5. The distributions are weighted in each channel and category by the $S/(S+B)$ ratio,

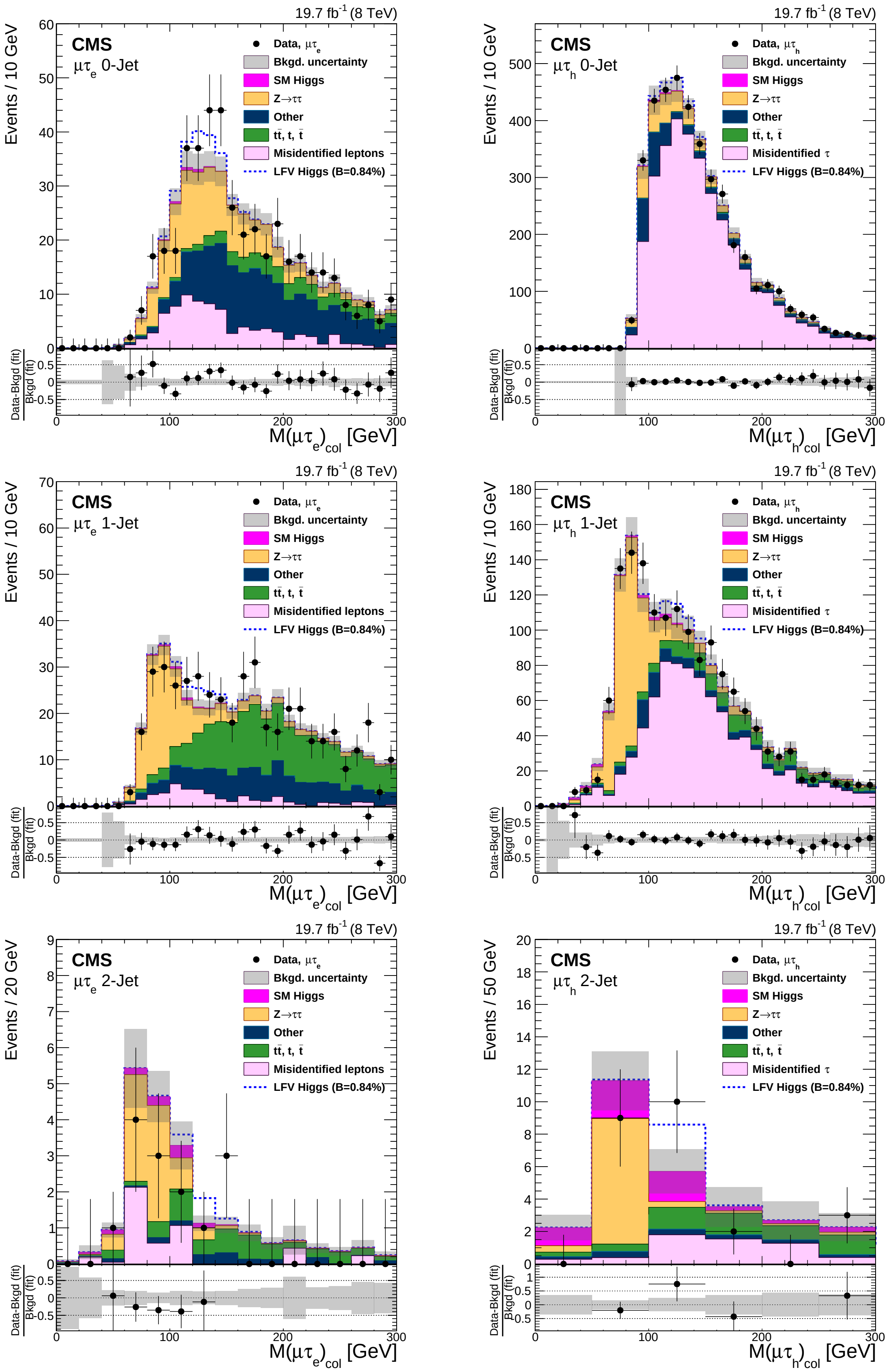

Figure 3: Distributions of the collinear mass M_{col} after fitting for signal and background for the LFV $H \rightarrow \mu\tau$ candidates in the different channels and categories compared to data. The bottom panel in each plot shows the fractional difference between the observed data and the fitted background. Top left: $H \rightarrow \mu\tau_e$ 0-jet; top right: $H \rightarrow \mu\tau_h$ 0-jet; middle left: $H \rightarrow \mu\tau_e$ 1-jet; middle right: $H \rightarrow \mu\tau_h$ 1-jet; bottom left: $H \rightarrow \mu\tau_e$ 2-jet; bottom right $H \rightarrow \mu\tau_h$ 2-jet.

where S and B are respectively the signal and background yields corresponding to the result of the global fit. The values for S and B are obtained in the $100 < M_{\text{col}} < 150$ GeV region.

Table 7: The expected upper limits, observed upper limits and best fit values for the branching fractions for different jet categories for the $\mathrm{H} \to \mu\tau$ process. The one standard-deviation probability intervals around the expected limit are shown in parentheses.

	0-Jet (%)	1-Jet (%)	2-Jets (%)
Expected Limits			
$\mu\tau_e$	<1.32 (±0.67)	<1.66 (±0.85)	<3.77 (±1.92)
$\mu\tau_h$	<2.34 (±1.19)	<2.07 (±1.06)	<2.31 (±1.18)
$\mu\tau$	<0.75 (±0.38)		
Observed Limits			
$\mu\tau_e$	<2.04	<2.38	<3.84
$\mu\tau_h$	<2.61	<2.22	<3.68
$\mu\tau$	<1.51		
Best Fit Branching Fractions			
$\mu\tau_e$	$0.87^{+0.66}_{-0.62}$	$0.81^{+0.85}_{-0.78}$	$0.05^{+1.58}_{-0.97}$
$\mu\tau_h$	$0.41^{+1.20}_{-1.22}$	$0.21^{+1.03}_{-1.09}$	$1.48^{+1.16}_{-0.93}$
$\mu\tau$	$0.84^{+0.39}_{-0.37}$		

8 Limits on lepton-flavour-violating couplings

The constraint on $\mathcal{B}(\mathrm{H} \to \mu\tau)$ can be interpreted in terms of LFV Yukawa couplings [4]. The LFV decays $\mathrm{H} \to \mathrm{e}\mu$, $\mathrm{e}\tau$, $\mu\tau$ arise at tree level from the assumed flavour-violating Yukawa interactions, $Y_{\ell^\alpha\ell^\beta}$ where ℓ^α, ℓ^β denote the leptons, $\ell^\alpha, \ell^\beta = \mathrm{e}, \mu, \tau$ and $\ell^\alpha \neq \ell^\beta$. The decay width $\Gamma(\mathrm{H} \to \ell^\alpha\ell^\beta)$ in terms of the Yukawa couplings is given by:

$$\Gamma(\mathrm{H} \to \ell^\alpha\ell^\beta) = \frac{m_\mathrm{H}}{8\pi}\left(|Y_{\ell^\beta\ell^\alpha}|^2 + |Y_{\ell^\alpha\ell^\beta}|^2\right),$$

and the branching fraction by:

$$B(\mathrm{H} \to \ell^\alpha\ell^\beta) = \frac{\Gamma(\mathrm{H} \to \ell^\alpha\ell^\beta)}{\Gamma(\mathrm{H} \to \ell^\alpha\ell^\beta) + \Gamma_{SM}}.$$

The SM H decay width is assumed to be $\Gamma_{\mathrm{SM}} = 4.1$ MeV [61] for $M_\mathrm{H} = 125$ GeV. The 95% CL constraint on the Yukawa couplings derived from $\mathcal{B}(\mathrm{H} \to \mu\tau) < 1.51\%$ and the expression for the branching fraction above is:

$$\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 3.6 \times 10^{-3}.$$

Figure 6 compares this result to the constraints from previous indirect measurements.

9 Summary

The first direct search for lepton-flavour-violating decays of a Higgs boson to a μ-τ pair, based on the full 8 TeV data set collected by CMS in 2012 is presented. It improves upon previously published indirect limits [4, 23] by an order of magnitude. A slight excess of events with a

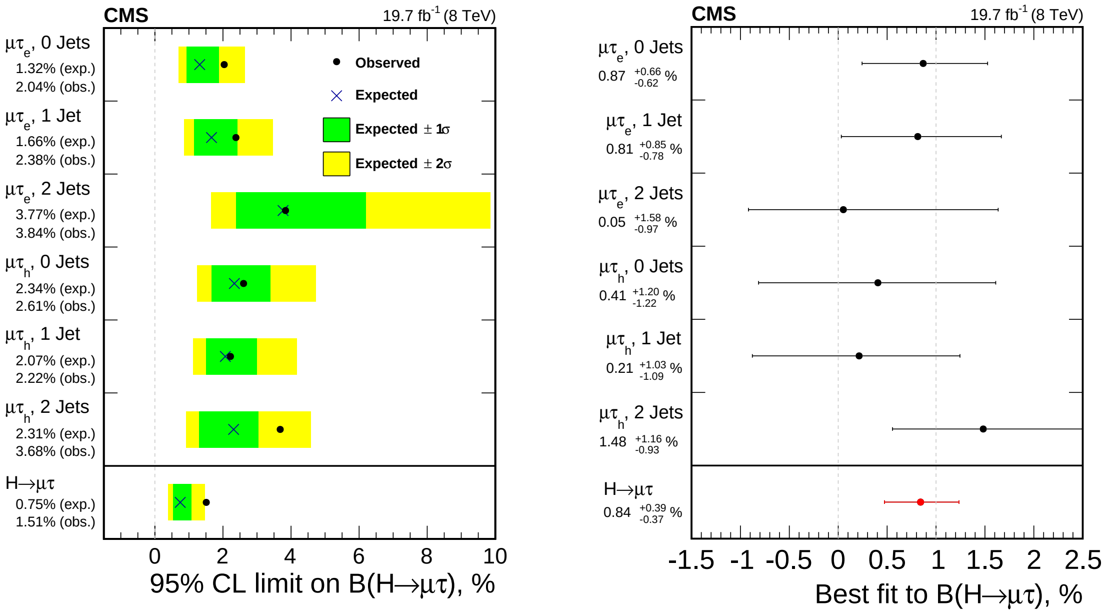

Figure 4: Left: 95% CL Upper limits by category for the LFV $H \to \mu\tau$ decays. Right: best fit branching fractions by category.

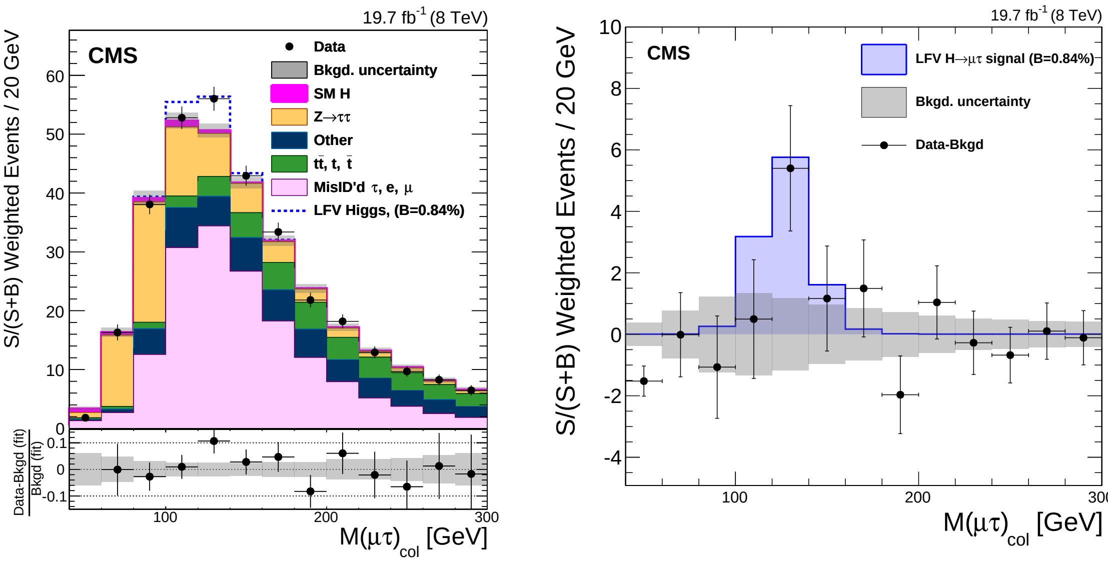

Figure 5: Left: Distribution of M_{col} for all categories combined, with each category weighted by significance $(S/(S+B))$. The significance is computed for the integral of the bins in the range $100 < M_{\text{col}} < 150\,\text{GeV}$ using $\mathcal{B}(H \to \mu\tau) = 0.84\%$. The MC Higgs signal shown is for $\mathcal{B}(H \to \mu\tau) = 0.84\%$. The bottom panel shows the fractional difference between the observed data and the fitted background. Right: background subtracted M_{col} distribution for all categories combined.

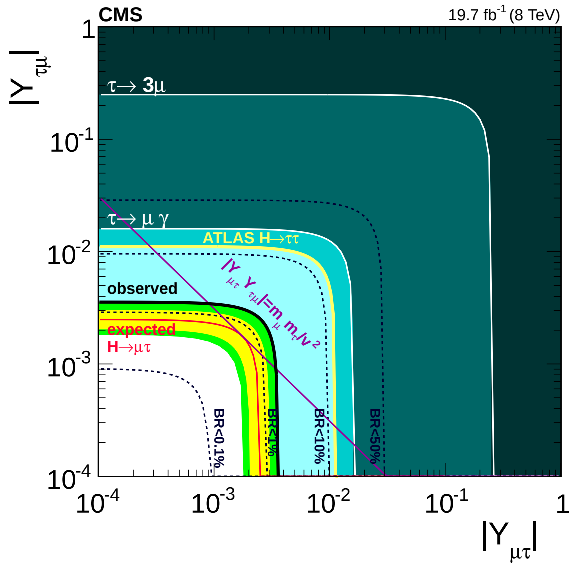

Figure 6: Constraints on the flavour-violating Yukawa couplings, $|Y_{\mu\tau}|$ and $|Y_{\tau\mu}|$. The black dashed lines are contours of $\mathcal{B}(\mathrm{H} \to \mu\tau)$ for reference. The expected limit (red solid line) with one sigma (yellow) and two sigma (green) bands, and observed limit (black solid line) are derived from the limit on $\mathcal{B}(\mathrm{H} \to \mu\tau)$ from the present analysis. The shaded regions are derived constraints from null searches for $\tau \to 3\mu$ (dark green) and $\tau \to \mu\gamma$ (lighter green). The yellow line is the limit from a theoretical reinterpretation of an ATLAS $\mathrm{H} \to \tau\tau$ search [4]. The light blue region indicates the additional parameter space excluded by our result. The purple diagonal line is the theoretical naturalness limit $Y_{ij}Y_{ji} \leq m_i m_j / v^2$.

significance of $2.4\,\sigma$ is observed, corresponding to a p-value of 0.010. The best fit branching fraction is $\mathcal{B}(\mathrm{H} \to \mu\tau) = (0.84^{+0.39}_{-0.37})\%$. A constraint of $\mathcal{B}(\mathrm{H} \to \mu\tau) < 1.51\%$ at 95% confidence level is set. The limit is used to constrain the Yukawa couplings, $\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 3.6 \times 10^{-3}$. It improves the current bound by an order of magnitude.

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